2014

Quantifying the impact of hurricanes, mid-latitude cyclones and other weather and climate extreme events on the Mississippi-Alabama Barrier Islands using remotely sensed data

Rebekah Danielle Jones
Louisiana State University and Agricultural and Mechanical College, rjon112@lsu.edu

Recommended Citation

Jones, Rebekah Danielle, "Quantifying the impact of hurricanes, mid-latitude cyclones and other weather and climate extreme events on the Mississippi-Alabama Barrier Islands using remotely sensed data" (2014). *LSU Master's Theses*. 3514.
https://digitalcommons.lsu.edu/gradschool_theses/3514

QUANTIFYING THE IMPACT OF HURRICANES, MID-LATITUDE CYCLONES AND OTHER WEATHER AND CLIMATE EXTREME EVENTS ON THE MISSISSIPPI-ALABAMA BARRIER ISLANDS USING REMOTELY SENSED DATA

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Department of Geography and Anthropology

by
Rebekah Jones
BA, Syracuse University, 2012
May 2014

“This is the way the world ends,

This is the way the world ends,

This is the way the world ends,

Not with a bang but a whimper.”

- T.S. Eliot, “The Hollow Men” (1925)

For Jackson.

ACKNOWLEDGMENTS

I have to first and foremost thank Robert Rohli, my advisor, for his continued support and discipline throughout my M.S. studies. Dr. Rohli gave me the focus and resources needed to bring this large undertaking to fruition.

For sharing their wealth of knowledge with me, a special thanks to professors Patrick Hesp, Fahui Wang, Kristine DeLong, Edward Richards, Andrea Miller, Shelly Meng and Robert Mann. I would also like to thank Judith Sylvester and Lei Wang, my thesis committee members, for their encouragement and constructive criticism.

I would like to thank my peers in the climate office for their thoughts and contributions in my studies. I would like to thank Jolene Williams and all of the Gulf Islands National Seashore staff for providing me with pertinent records and data for this project.

I have to thank Drs. Kevin Robbins and Barry Keim for the opportunity to work with the Southern Climate Impacts Planning Program and for their training and expertise, which has made me a better communicator, researcher and employee. I am forever indebted to Dr. Lynne Carter, my boss and friend, who gave me purpose in being at LSU.

I would like to thank my family and friends for their support as I continue my education. A special thanks to my partner in work and life Jacob Romer, who guided my through many of the statistical problems I encountered. Last but not least, thank you to my son, Jackson, for whom I do everything, for always encouraging me to do my work and be a better student, person, and mother.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Recent high-profile hurricanes have demonstrated the destructiveness of extreme events on coastal landscapes to the world. Barrier islands across the planet are disappearing, exposing vulnerable coastal cities to the damage caused by extreme events. Growing resolve among scientists regarding climate change's connection to tropical cyclones heightens the concern around intensifying extremes and landscape dynamics.

This study uses more than 600 Landsat images to examine the role of extreme events on barrier island morphology on four of the Mississippi-Alabama barrier islands from 1972-2014. Each island, West Ship Island (WSI), East Ship Island (WSI), Petit Bois Island (PBI), and Sand Island, was measured for area in hectares (ha) 14 times per year on average with higher temporal resolution before and after hurricanes, allowing for a high-resolution statistical history of surface area change and the quantification of the impact of extreme weather events.

The results reveal that extreme events, specifically hurricanes, mid-latitude cyclones, and thunderstorms, shape the islands more than gradual erosion and accretion processes across all islands. The results also show that hurricanes trigger accelerated erosion beyond landfall. Catastrophic events caused 54-59% of all land area change on the islands during the study period. Hurricanes caused 26-37% of all change across the islands, thunderstorms 11-13%, and mid-latitude cyclones 11-14%. Three of the islands lost at least one-quarter of their 1972-1973 areas: WSI 25%, ESI 39%, and PBI 38%. WSI, ESI, and Sand Island are all in post-Katrina (2005) regrowth periods while PBI has destabilized and continues to experience net erosion. The results of this study can serve the Gulf Islands National Seashore in long-term environmental planning.

1. INTRODUCTION

1.1 Barrier Islands

Barrier islands are coastal landforms that form as narrow strips of land parallel to a coastline, typically made up of quartz or other fine-grained sand. Like in the Mississippi Sound, this process typically results in chains of islands across longshore-drift coastlines (Hayes 2005). Barrier island dynamics and morphology depend on the tidal range, wave energy, sediment supply, sea-level trends, and climatology of the region. Barrier islands border 13% of the world’s coastlines (Smith et al. 2010) and parallel 3700 km of 18 U.S. states (Keqi and Leatherman 2011). The Mississippi-Alabama Barrier Islands, located in the northern Gulf of Mexico, are comprised of transgressive and regressive beaches, migrating shoreward and westward along the coastline.

Barrier islands provide a first line of defense against hurricanes as storm surge buffers, protecting lives and property across the mainland (Otvos and Carter 2008). Barrier islands also supply important marine habitats and furnish beaches for tourism and recreation. Protecting the Mississippi-Alabama Barrier Islands has been the mission of the Gulf Islands National Seashore (GINS) for more than 40 years. The islands have great economic, historical, and cultural value beyond storm surge protection, and their loss would create a ripple effect through local communities (GINS 2013). This research could assist GINS by providing an in-depth analysis of the morphological changes of four of the islands. Understanding how the islands have changed over time will assist the GINS team in coordinating efforts based on the natural fluctuations and overall trends in island change, planning dredging projects at the most effective times, monitoring the impacts of various weather events, and anticipating future change based on observed historical patterns.

The Mississippi-Alabama Barrier Islands, comprised of Cat, Ship (West and East), Horn, Petit Bois and Dauphin, form a 105 km long chain located 11-20 km south of the mainland coastlines of Mississippi and Alabama (Figure 1.1). The island system rests inside the Mississippi Sound, a 4-20 km wide and 1-4 m deep bay that drains the Mobile River drainage basin - the fourth-largest river basin in the country (Otvos and Carter 2008). Four of the islands in the system were selected for this research project: West Ship Island (WSI), East Ship Island (ESI), Petit Bois Island (PBI), and a human-constructed, currently-unnamed island forming off the western spit of PBI within the Pascagoula Ship Channel, nicknamed "Sand Island" by the GINS staff[1]. The islands outline the surf zone of the northern Gulf Coast, reducing wave action in the littoral zone, where relic islands dot the Pleistocene Ridge.

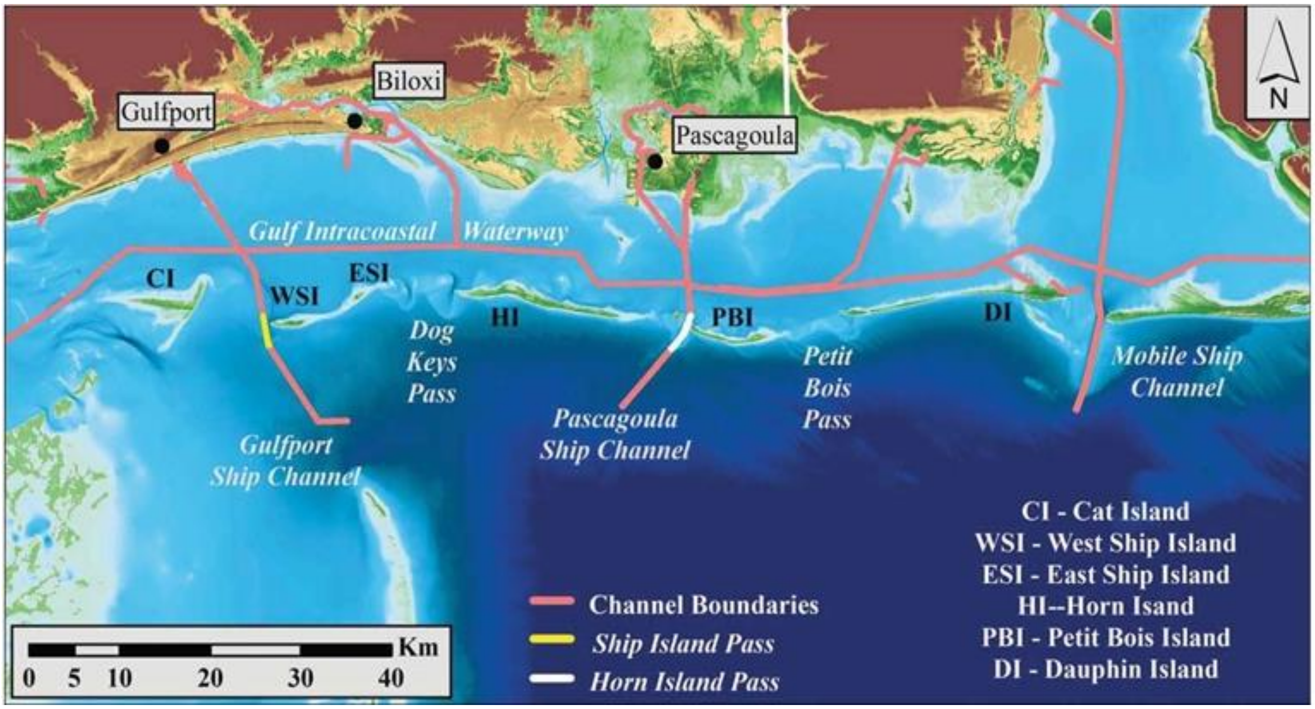

Figure 1. 1 The Mississippi-Alabama Barrier Islands and corresponding channels (Byrnes et al. 2013), showing WSI, ESI, and PBI south of Biloxi and Pascagoula, respectively.

---

[1] Sand Island is also called Spoil Island and West Petit Bois Island by various stakeholders, including members of the GINS staff, although the most common name among the GINS staff and locals is still Sand Island (Williams 2013).

The region experiences subtropical climate conditions, with a record high of 40°C recorded in August 2000, and a record low of -13°C recorded in January 1963. The area receives 160 cm of precipitation each year, on average (Figure 1.2). Winters are mild and wet with snow rarely occurring, and high and low temperatures averaging 17°C and 8°C, respectively. Summers are hot and humid, with average high and low temperatures of 32°C and 23°C, respectively. Overall, the area experiences humid, hot, and wet conditions, influenced by its latitude, flat terrain, and proximity to the Gulf of Mexico. The study area also experiences a variety of extreme weather events, including cold and warm fronts, hurricanes, tornadoes, derechos, floods, and extreme wind.

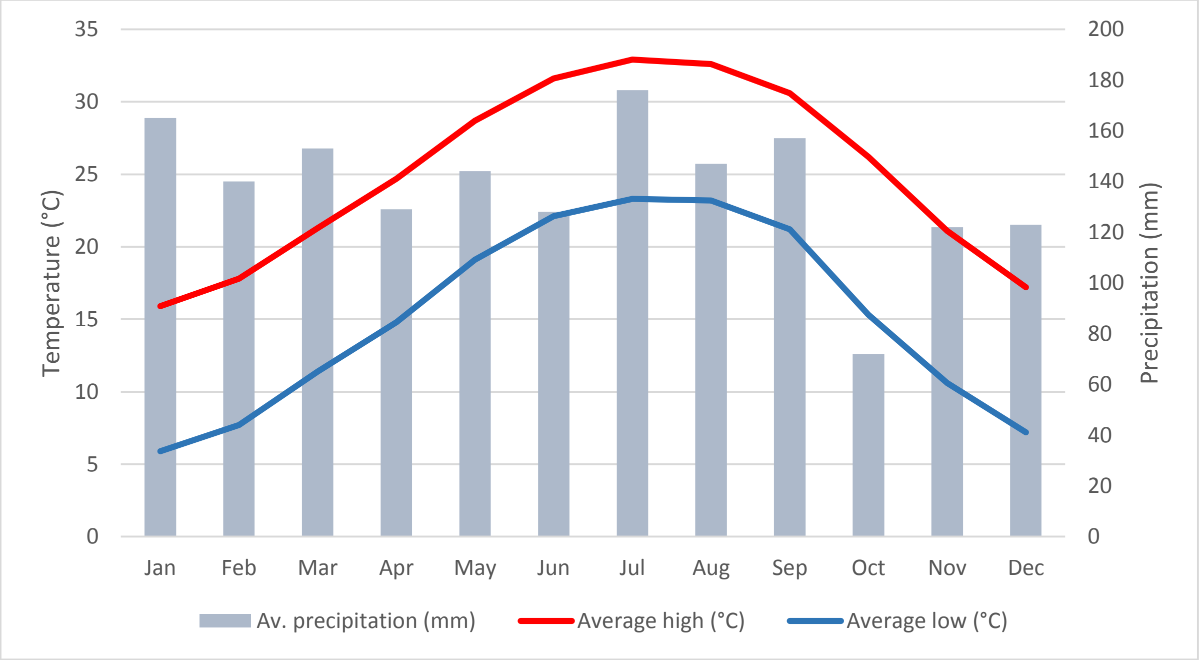

Figure 1.2 Profile of average high and low monthly temperatures and average monthly precipitation, for Biloxi, Mississippi.

Each of the islands offers unique challenges and opportunities in studying how extreme weather events influence barrier island dynamics. The four islands studied in this paper are separated by the largest island in the system (Horn Island), experience different degrees of human interaction and development, and are most easily measured in the analysis process. By choosing islands that are at different stages in the sediment-building process and separated by kilometers of beach and ocean, system-wide changes can be analyzed on a high-resolution temporal scale. Climate signals can then be analyzed by examining the system as a whole and the relative impact on each individual island.

All of the islands have undergone significant morphological change during the last 200 years. WSI and ESI formed as one large island that had split several times since the Civil War, but always reattached, until the island was permanently bisected by Hurricane Camille in 1969. The channel left behind by Camille has since been named the “Camille Cut.” The two islands were later renamed West Ship Island and East Ship Island. PBI experienced rapid transformation and westward translocation as a result of littoral drift even before the research period started and continues to experience that pattern today. Sand Island did not exist during the first two years of the study period, and has grown to be larger than ESI. Sand Island has experienced steady growth, retaining eroded sediment pushed westward off PBI.

This project spans 40 years for WSI, ESI, and Sand Island, and 30 years for PBI. Availability of Landsat imagery was the primary reason for the selected time period, as well as imagery resolution, historical imagery and data availability, and consistency of data. Using more than 600 Landsat images, the project aims to quantify the impact of catastrophic events on each of the islands, specifically examining tropical cyclones, thunderstorms, and mid-latitude cyclones. The primary research objective seeks to determine whether long-term events or gradual changes have been more influential than singular catastrophic events in shaping the islands. This study also considers trends in sea level, the geomorphological evolution and systematic failure of the island chain, and seasonal and inter-annual variability.

1.2 Thesis Purpose

The causes of morphological change on the Gulf Coast Barrier Islands have been the focus of multiple research projects in the last two decades (e.g. Morton 2008, Otvos and Carter 2008, Flocks and DeWitt 2009, Morton 2010). Multiple LIDAR and Landsat analyses have revealed changes on decadal scales with particular attention to tropical cyclone activity and volumetric adjustment (e.g. Bonisteel-Cormier et al. 2011, Carter et al. 2011). The theorized primary drivers of change observed on the islands range from general gradual erosion to cold fronts. Penland et al. (2005) hypothesized that the islands are thinning in place due to a combination of sea level rise, sediment depletion, and general erosion. Rosati and Stone (2009) suggested that landward retreat resulted primarily from relative sea level rise, causing the island to "rollover on itself." Others (e.g. McBride et al. 1995) asserted that barrier island evolution was driven primarily by lateral migration. Leatherman (1979, 1983) and Schwartz (1973) found that inlets, overwash, and aeolian transport were the dominant processes for barrier island migration. Morton (2008) observed that Ship Island lost half its area due to island narrowing, unequal lateral transfer, and island segmentation, and that general island area loss has been caused by unequal updrift erosion and downdrift deposition. However, Morton (2010) also noted that hurricanes have a "profound impact" on island morphology.

Others attribute a larger portion of loss to extreme weather events than Penland et al. (2005), Rosati and Stone (2009), McBride et al. (1995), Leatherman (1979), Schwartz (1973), and Morton (2010). Leatherman (1983) determined that neo-catastrophism, or the extreme event, played a "significant" role in geomorphologic change. Nummedal et al. (1980) suggested that hurricanes are a "major, perhaps the dominant agents in the development of barrier island morphology along the northern and western shores of the Gulf of Mexico." Nummedal et al. (1980)

went on to say that storm surge was the primary factor in determining erosion caused by hurricanes. Stone et al. (2004) determined that cold fronts over a two-year period caused more damage than six examined hurricanes over the same time period on Santa Rosa Island, Florida.

Despite the extensive research into coastal processes, however, the degree to which the rare event or gradual change has driven these forces has remained largely unquantified (Marriner et al. 2010). Previous studies lack the temporal resolution necessary for modeling or quantitative analysis. Morton (2008) used 15 data points taken from a variety of sources, including historical data, aerial photography, LIDAR, and topographic maps to gauge general trends in island area (Figure 1.3). Stone et al. (2004) analyzed 26 data points over a two-year period using land surveys to measure the response of WSI and neighboring Santa Rosa Island, Florida, to tropical cyclones and cold fronts. The current study uses more than 600 Landsat images to determine surface area change from 1972-2014, and aims to attribute all losses and gains observed between data points to either non-extreme-event-induced erosion and accretion, or to extreme events due to tropical cyclones, mid-latitude cyclones, and thunderstorms, or to anthropogenic impacts.

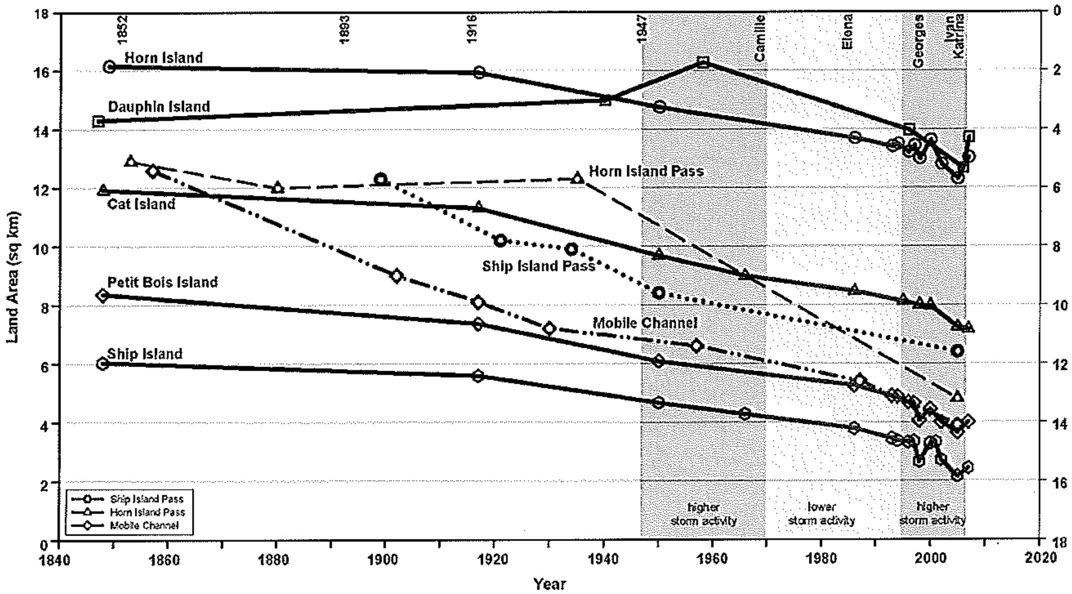

Figure 1.3 Morton’s (2008) calculated barrier island change from the 1850s through 2007.

1.3 Island Profiles

The Mississippi-Alabama Barrier Islands sit atop a Pleistocene ridge in the northern Gulf of Mexico, with minimal wave energy along the shore and beaches dotting the coastline. A low tidal range in the northern Gulf Coast, averaging less than 0.5 meters (m), exhibits limited seasonal range: 0.4 m in summer and 0.6 m in winter (Rosati et al. 2007). During most of the year, predominant winds from the southeast drive longshore currents to the west, which causes a natural westward migration, called translocation, of the island system (Cipriani and Stone 2001). The Gulf sides of the islands are comprised of regressive and transgressive beaches defined by littoral drift from the Gulf of Mexico. The landward sides of the islands are a mix of tidal flats, marshes, swamps, lagoons, coastal dunes, and beaches, many of which are artificial or part of a nourishment project (Gerdes et al. 1980). These beaches are fed by the Gulf Intracoastal Waterway, an ocean circulation system confined within the barrier island system.

Ship Island historically consisted of two strandplain islands (broad belts of sand along a shoreline with a surface exhibiting well-defined parallel or semi-parallel sand ridges separated by shallow swales) connected by a narrow, low barrier neck that was often submerged during periods of high tropical cyclone activity (Otvos and Carter 2008). Otvos and Giardino (2004) found that the ESI strandplain "may be the relict recurved west top of a long-extinct old barrier." The multiple incisions and cuts at the island center, made permanent by Hurricane Camille (1969), appeared throughout the island history (e.g. 1906, 1926, and 1949). Ship Island is most vulnerable to storm surge and wave action due to its location between the east-west trend of the island chain and the north-south trend of the Chandelier Islands (Morton 2008). According to Byrnes et al. (2013), "East Ship (erosion and overtopping) has been so frequent since 1969 that the island appears in danger of complete degradation within the next 10-20 years."

All of the islands were incorporated into the GINS in 1972. GINS operates under the National Park Service and closely monitors activities on most of the islands in the system. GINS prohibits many activities on the islands, including removing plants and animals from the island, bringing glass onto the island, and accessing some beaches (Williams 2013). WSI opens throughout the year for recreational purposes, mostly swimming and boating, but limits human exposure outside of designated swimming areas. ESI became entirely private in 2005 and does not allow boating, fishing, or swimming. Dauphin Island has been developed as an urban area outside of Mobile, though since Hurricane Katrina (2005) divided PBI into two pieces, development has been confined to its eastern half, allowing for rapid westward translocation of sediment from Dauphin to PBI. PBI remains undeveloped, though open to commercial and recreational activities, such as fishing and swimming. Horn Island separates the two study areas and is the largest and the most forested island in the system. It remains undeveloped, though open to commercial and recreational activities. Sand Island was designed as a catchment for sediment eroding from PBI into the Mississippi Sound, but took on a life of its own in the 1970s, growing more than 900 percent during the study period.

1.4 Climatological Profile

The study area remains largely isolated by the Gulf of Mexico and the Mississippi Sound, and experiences unique weather phenomena. The most common type of extreme weather event the study area experiences is thunderstorms (Rosati and Stone 2009). Mid-latitude cyclones, or winter storms, also frequently cross the area, causing high winds and rains as well as freezing temperatures (Sherman-Morris et al. 2012). Hurricanes are the rarest but most powerful extreme weather event occurring in the area, with return periods for tropical storms, all types of hurricanes, and hurricanes of a Category 3 or higher strength on the Saffir-Simpson scale (Table 1.1) making landfall every four, 10, and 52 years, respectively (Keim et al. 2007). Each of these weather events results from multiple local, regional, and global processes, ranging from global ocean temperatures to the southern extent of the polar vortex.

Table 1.1 Saffir-Simpson Hurricane Scale.

Category	*Winds (km/hr)*	*Damage*	*Hurricanes observed in the current study*
1	119-153	Minimal	Agnes (1972), Babe (1977), Bob (1979), Allison (1995), Danny (1997), Lili (2002), Claudette (2003), Cindy (2005), Humberto (2007), Isaac (2012)
2	154-177	Moderate	Georges (1998), Frances (2004), Gustav (2008)
3	178-208	Extensive	Eloise (1975), Elena (1985), Andrew (1992), Erin (1995), Bret (1999), Isidore (2002), Ivan (2004), Dennis (2005), Katrina (2005), Rita (2005)
4	209-251	Extreme	Frederic (1979), Opal (1995), Emily (2005)
5	>252	Catastrophic	Anita (1977)

Individual thunderstorms are relatively small systems sometimes but not always associated with fronts; they are typically less than 24 km in diameter and last less than an hour. A cold front allows cumuliform clouds to form with large vertical extents, which produce intense precipitation and thunderstorms (Christopherson 2009). Cold fronts result in high-frequency waves and an elevated water level, and occur 20-40 times a year (Sherman-Morris et al. 2012). Cold fronts have brought deep-water wave heights of 2-4 m, a frontal surge of 0.3-0.4m^{-1}, winds from the north of 55 km/hr, for a period of 12-24 hours (Rosati and Stone 2009). Cold front passage was observed to erode the Gulf-side sand and deposit it and the bayside marsh (Rosati and Stone 2009).

Individual thunderstorms can occur in larger, more organized clusters in which the clusters themselves can last several hours. Although they are small, about 10% of the more than 100,000 thunderstorms that occur each year in the United States are classified as severe (NOAA 2013); most of these are part of organized storm systems. The National Weather Service (NWS) classifies a thunderstorm as severe when it produces winds exceeding 93 km/hr, hail 1.9 cm in diameter, or a tornado (NWS 2012). Updrafts and downdrafts intensify each other by reinforcing each other during severe thunderstorms (Christopherson 2009). Severe thunderstorms usually form in clusters over large areas, forming a mesoscale convective system (MCS). A MCS can last up to several days and are fairly common in North America (Christopherson 2009). MCSs sometimes form as squall lines, or solid bands of strong thunderstorms, ahead of troughs due to significant atmospheric moisture and upper level divergence (Christopherson 2009). Squall lines can lead to hail and high winds. Squall-line thunderstorms form as large numbers of individual violent storm cells arranged in a linear band, typically about 500 km in length (Christopherson 2009). Squall lines usually occur in the warm sector of a mid-latitude cyclone. As the downdrafts in a squall reach the ground they form wedges of cold, dense air called a gust front (Christopherson 2009).

Severe thunderstorms can also form from supercells, or intense individual thunderstorms with a single updraft zone (Christopherson 2009). Supercells are smaller than squall lines and MCSs and last between two and four hours, but are typically more violent and produce large tornadoes. Supercells also experience large-scale rotation. The conditions needed to form a severe thunderstorm are wind shear, high water vapor content in the lower troposphere, some mechanism to trigger uplift, and potential instability. Thunderstorms account for about 70% of the total annual rainfall over the south-central United States (Chagnon 2001). South Mississippi experiences more than 60 thunderstorm days per year (NCDC 2012). Thunderstorms also produce downdrafts, derechos, and microbursts (Christopherson 2009). Across the United States, derechos are most common from May through July (NCDC 2012). The frequency of derechos in the U.S. Southeast peaks from September through April.

Thunderstorms and hurricanes often produce tornadoes, which are zones of extremely rapid, rotating winds beneath the base of a cumulonimbus cloud (Christopherson 2009). Tornadoes result from extreme differences in atmospheric pressure over short distances. In theory, tornadoes can form in any weather-frontal boundary, squall line, or MCC, although their presence on islands has been ill-documented (Shu et al. 2012). Waterspouts occur over warm bodies of water and are smaller and weaker than tornadoes, although they can have wind speeds of up to 150 km/hr (Christopherson 2009). Waterspouts can be common in island regions. For example, waterspouts occur almost daily around the Florida Keys (Golden 1974). While some waterspouts form from tornadoes that move over water, most develop as warm water heats the air from below and causes it to become convectively unstable. An outbreak of waterspouts in April 2012 near Biloxi, Mississippi, caused minor damage to coastal structures (Figure 1.4).

Figure 1.4 A waterspout spotted offshore just south of Grand Isle, Louisiana (National Oceanographic and Atmospheric Administration).

Mid-latitude cyclones, also called winter storms or nor'easters, can last a week or longer, travel large distances, and bring heavy precipitation (Christopherson 2009). Some of the mid-latitude cyclones examined in this report covered nearly all of the continental United States. Cyclogenesis, the process that creates mid-latitude cyclones, occurs when a disturbance between the polar front boundary, cold easterlies, and warmer westerlies develops along the boundaries. The cold air pushes southward behind a cold front and the air behind the warm front moves northeastward, creating a counterclockwise rotation around a weak low pressure system (Christopherson 2009). The low pressure eventually deepens and forms strong warm and cold fronts from the original polar front. Convergence from the low pressure leads to uplift and cloud formation as linear bands of deeper cloud cover develop along the frontal boundary (Figure 1.5).

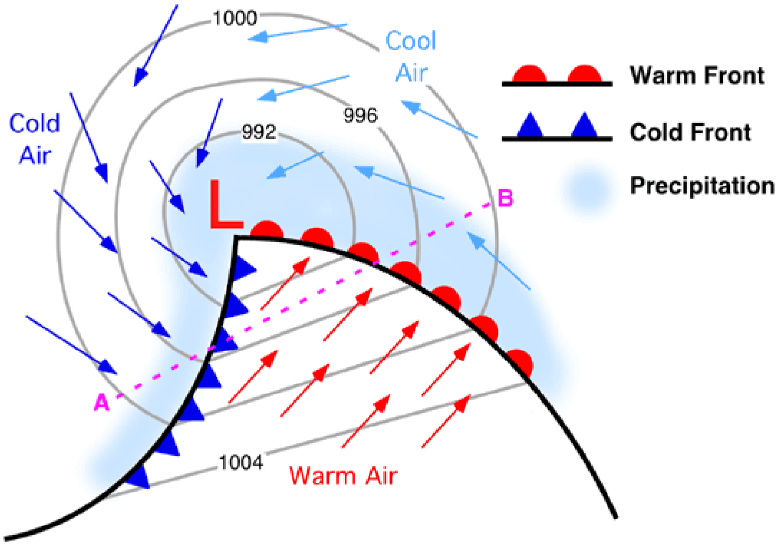

Figure 1.5 The anatomy of a mid-latitude cyclone (Pidwirny 2006).

The average size of a mid-latitude cyclone ranges from 1500-5000 km in diameter, as opposed to hurricanes which range from 200-1000 km in diameter (Shu et al. 2014). The Gulf Low track of winter storms occurs at the thermal boundary between the cold surface of the land and the warmer temperatures on the Gulf of Mexico. The Gulf Low typically produces more precipitation than most other cyclone tracks because of its proximity to the ocean (Figure 1.6) (Pidwirny 2006).

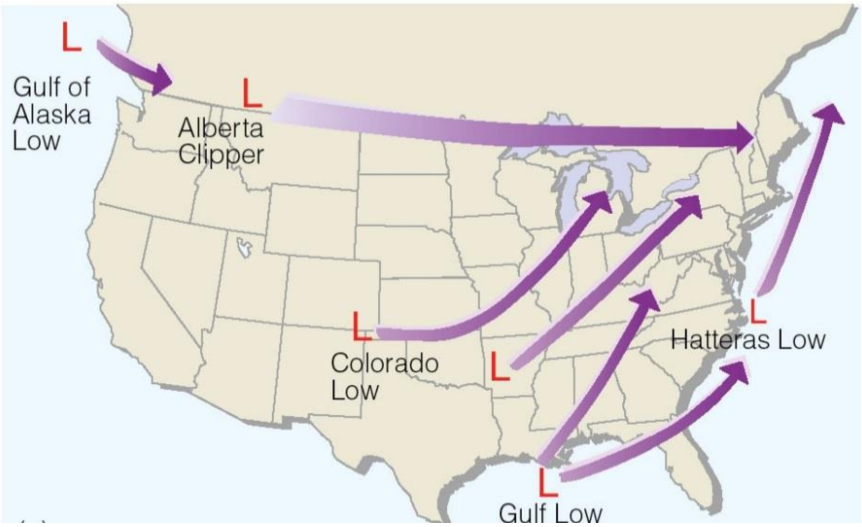

Figure 1.6 Common paths of mid-latitude cyclones (Pidwirny 2006).

The "Storm of the Century" (March 12, 1993) covered most of North American, and eroded 20 ha from PBI and 5 ha from Sand Island (Figure 1.7). Although not among the most severe 15 events to impact the islands, the strong mid-latitude cyclone did register as a major event. That particular system had a minimum pressure of 960 mb – lower than 80% of tropical cyclones (NCDC 1993). The storm produced strong winds and record-breaking precipitation, as well as extremely low temperatures for the Gulf Coast region. Freezing temperatures kill vegetation, which allows sand and dirt to be more easily blown or washed away from the islands. Prolonged periods of extremely cold temperatures, like those observed during the Storm of the Century, can kill plants and delay vegetation regrowth. The IPCC determined that since the middle of the twentieth century, mid-latitude cyclones have been traveling farther south (IPCC 2007).

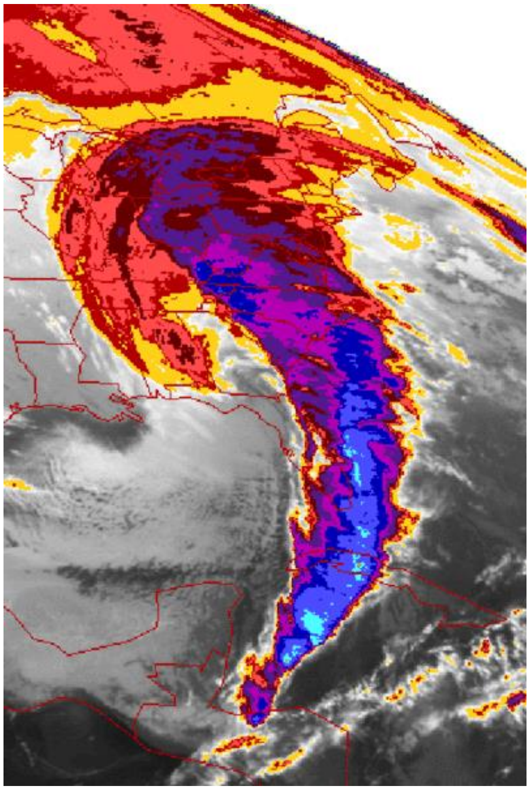

Figure 1.7 The 1993 "Storm of the Century" Mid-latitude cyclone on March 12, 1993. Mid-latitude cyclones are often identifiable by their comma-shaped cloud mass, visible on satellite imagery like that above (National Weather Service).

Thunderstorms and winter storms occur regularly and with varying levels of severity, but hurricanes are the defining extreme weather event for the northern Gulf of Mexico. Hurricanes have sustained winds of 120 km/hr or greater. Hurricanes have lower wind speeds than tornadoes and are usually about one-third the size of mid-latitude cyclones. But hurricanes are much larger than tornadoes and last longer, often spinning off tornadoes themselves, and have a pressure gradient about twice as great as mid-latitude cyclones (NOAA 2013). Bands of intense convection, separated by weaker uplift and descending air, spin counter-clockwise around the storm center, allowing severe weather to reach hundreds of kilometers from the storm center (Fitzpatrick 2014).

Hurricanes can take weeks to develop, giving coastal communities more warning than a tornado, but often leaving catastrophic damage in their wake. Hurricanes start as tropical disturbances, which are disorganized groups of small clusters of thunderstorms with weak pressure gradients and no discernable rotation. They draw their energy from the warm oceans, which justifies why they form near the equator and often intensify in the warm Gulf. The minimum threshold temperature for hurricanes to form is 27°C (NOAA 2013). Once a tropical disturbance moves across the Atlantic or Gulf, it releases latent heat once evaporated water begins to condense and form clouds, which warms the area around the disturbance. Air density inside the disturbance decreases as a result, dropping surface pressure (NOAA 2013). As the cold air rushes underneath the rising warm air wind speeds increase. Hurricanes form in the northern hemisphere, so the northeast trade winds and Bermuda-Azores anticyclone push the storms westward through the Atlantic, as rotation within the storms strengthens. The incoming winds pull in additional moisture that condenses to form clouds and releases additional latent heat in the process. Hurricanes are essentially giant heat engines that can self-sustain and grow rapidly under optimum conditions, including warm ocean surface temperatures and minimal wind shear.

The Mississippi Gulf Coast experienced several major hurricanes prior to the start of the research study period. In fact, of the 10 most severe landfalling Atlantic hurricanes in the United States since instruments for monitoring wind speed and size have been available, seven have struck near the study area: Carla (1961), Betsy (1965), Camille (1969), Katrina (2005), Opal (1995), an unnamed hurricane that struck Miami, Florida, and then Mobile, Alabama, as a Category 3 in 1926, and Audrey (1957). Carla made landfall as Category 4 (230 km/hr) on Matagorda Island, Texas, with a minimum pressure of 931 mb. Betsy struck as a Category 3 (179 km/hr) and produced 330 mm of rain in the New Orleans, Louisiana, area. Betsy was the first hurricane in the United States to cost more than $1 billion in damage. Hurricane Camille struck Biloxi, Mississippi, in August 1969 as a Category 5 with sustained 305 km/hr wind speeds. The 1926 hurricane produced a 4.6

m storm surge. Audrey made landfall on the Texas-Louisiana border, spawning 23 tornadoes in Mississippi and Alabama, dumping 280 mm of rain and producing a storm surge of nearly 2 m. Since all of the aforementioned storms occurred before the launch of Landsat 1 in 1972, the damage the islands incurred as a result those events have not considered in this study.

Even though five of seven of these storms occurred before the study period started, their effects likely linger into the research period. However, just because these storms were the overall most intense does not mean they were the most intense in the study area. A hurricane’s impact on any given place depends on the orientation, direction, wind speed, size, duration, precipitation amount, and storm surge. A storm with a 3 m storm surge may devastate an area east of its track, but barely impact areas on its western quadrant. In general, the area to the east of the landfall experiences the most amount of damage, in a vulnerable position for northern hemisphere storms on east-west oriented coastlines because the counterclockwise rotation around the storm will accumulate storm surge onshore to the east of the eye. The impact of a hurricane on a beach front also depends on the time of year the hurricane strikes and the state of vegetation at that time.

According to Morton (2010), the most common impact of hurricanes is the creation of washover terraces. A washover terrace forms during an overwash event, when many washover fans are formed so close that their edges become indistinct or when overwash by runup occurs over a low, uniform beach. Morton (2010) also showed that patterns of morphological change caused by hurricanes are “mostly independent of storm parameters,” including path, intensity, proximity, and shelf duration. Rosati and Stone (2009) determined that storm response depends on the minimum barrier elevations relative to maximum storm sea level elevation, the duration of the maximum storm sea level elevation, and the amount and type of vegetation coverage of the barrier. Rosati and Stone (2009) found that hurricanes tended to strip sand entirely from the islands and deposit it in the bay, which then could be transported back into the Gulf via return flow through breaches as the storm surge decreased. The current study finds that hurricane parameters, particularly storm surge, do correlate with event erosion.

Multiple global atmospheric and oceanic sources of climate variability have an impact on the Mississippi-Alabama barrier islands. Impacts of each are often difficult to ascertain, because the various phenomena occur simultaneously and because the impacts of an individual type of phenomenon differ from one event to the next. These mechanisms affect everything from hurricanes to overall climate conditions. Sea level has been examined in terms of its relative impact on island morphology. Sea level records are “highly correlated” and show “the same trends in the relative rise in sea level and the same details of the short-term secular variations,” though the study does not quantify the degree of the impact (Morton 2008). The current study quantifies sea level’s relationship with area for each of the islands and within each time period.

Three primary systems are the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO). While other global mechanisms certainly have impacts on the region, ENSO, PDO, and AMO impact the climatology of the region more than any others. El Niño-Southern Oscillation (ENSO) cycles between positive (warm) and negative (cool) ocean temperatures in the central equatorial Pacific, with warmer events there called El Niño and cooler events called La Niña (Christopherson 2009). ENSO influences hurricane activity (NOAA 2013). Typically La Niña (cooler) years bring more hurricanes to the Atlantic basin, while El Niño (warmer) years bring more typhoons to the Pacific basin (NOAA 2013). If wind shear is too strong (above 8 ms^{-1}), hurricane development is less likely (NOAA 2013). La Niña reduces the vertical wind shear in Atantic basin tropical cyclones (Christopherson 2009). ENSO cycles also influence where hurricanes form in the basin. Hurricanes most often form from African easterly waves in the tropical eastern north Atlantic during La Niña years, increasing the likelihood of a hurricane becoming a major storm. On the other hand, during an El Niño event, the North American section of the polar front jet stream extends into the southeastern United States, increasing the odds of severe weather outbreaks. During La Niña years, the polar front jet stream tends to remain farther north over North America. During El Niño years, the Southeast tends to experience a wet and cool climate, and during La Niña years it is more likely to be warm and dry (NOAA 2013), but each El Niño (and La Niña) event is unique in magnitude and impact.

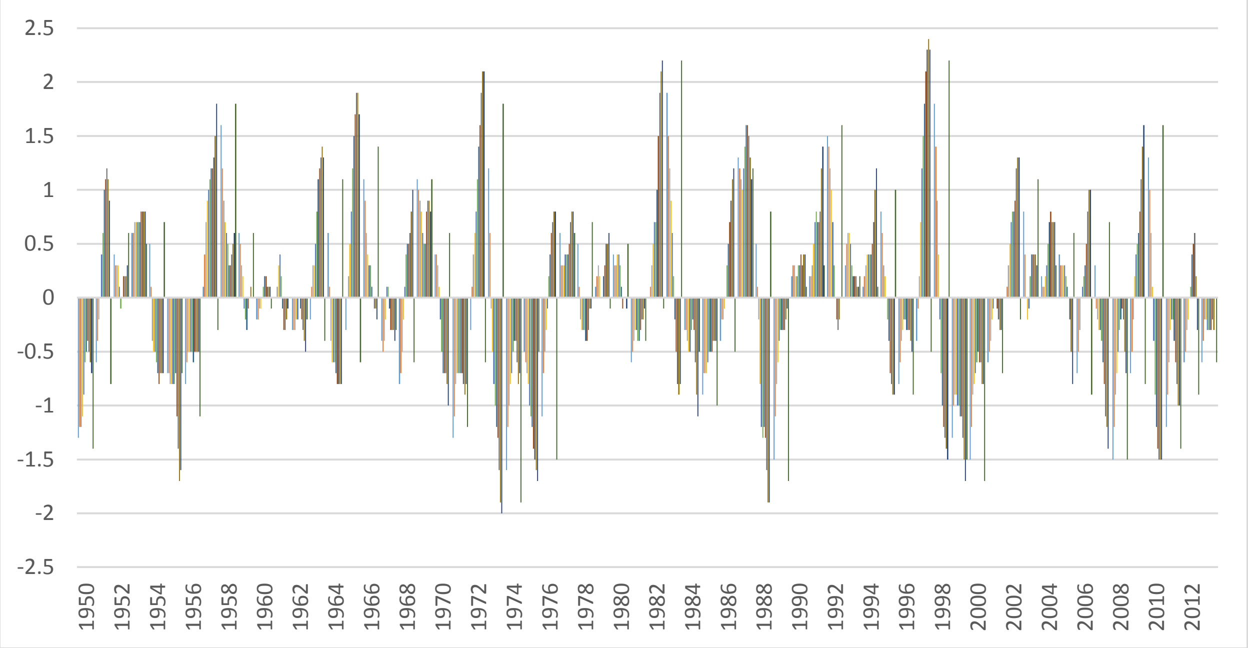

Figure 1.8 ENSO cycles from 1950 to 2012, measured in departure from normal (C°) (NCDC 2013).

ENSO phases during the study period correlated with tropical storm activity, which impacts island area change. Positive increases in temperature reflect an El Niño phase, while negative figures reflect a La Niña phase (Figure 1.8). Much of the highly-stable periods of the islands morphological history happened in strong El Niño phases, when hurricane activity in the Atlantic basin typically decreases (NOAA 2013). Likewise, periods of extreme variability in surface area occurred during multiple, severe La Niña phases, when hurricane activity increases. Years when the temperature range is below the threshold of +/- 0.5 C° for the Oceanic Niño Index (ONI) are considered "neutral" periods. The data above for the ONI are based on a three-month running mean of Extended Reconstructed Sea Surface Temperature (ERSST) anomalies in the El Niño (NASA 2013):

> Whether or not an El Niño event is identified during the early summer, as it was in 1997, the potential for a major outbreak of U.S. hurricanes in an El Niño year is significantly decreased. The chance of a major U.S. hurricane is reduced as well (NOAA 2013).

The AMO is an oscillation in sea surface temperatures which occupies a large percentage of the Atlantic basin, which has correlated with an increase in tropical cyclone activity when it shifted from cool to warm around 1995 (NOAA 2013). The AMO lasts between 20 and 40 years at a time and changes ocean temperatures by about 0.5C° between extremes (Figure 1.9) (NOAA 2013). During warm phases of the AMO, hurricane activity in the Atlantic basin generally increases. The number of tropical cyclones that reach hurricane status during a warm phase is about twice as many as cool phases (NOAA 2013). Since 1995, the AMO has been in a warm phase (NOAA 21013). A change from cool to warm AMO occurred around 1995, when Atlantic tropical cyclone activity increased, after being in a cold phase for more than 30 years:

> During warm phases of the AMO, the numbers of tropical storms that mature into major hurricanes is significantly greater than during cool phases, at least twice as many. Since the AMO switched to its warm phase, circa 1995, major hurricanes (Category 3 or above on the Saffir-Simpson Hurricane Scale) have become much more frequent… (NOAA 2013).

The PDO experiences more overall variability than the AMO, shifting temporarily to warm from cool and vice versa throughout the time period (Figure 1.10). The PDO, like the AMO, is a 20-to-30-year event describing changes in temperature in the Pacific basin (NOAA 2013). During positive phases, or warm phases, of the PDO, the U.S. Southeast experiences below average temperatures and above average precipitation. The PDO shifted from a warm phase to a cold phase in 1945-1946 and lasted through 1977. The PDO shifted again in 1997-1998 to a cool phase, where it has remained since that time (NCDC 2013).

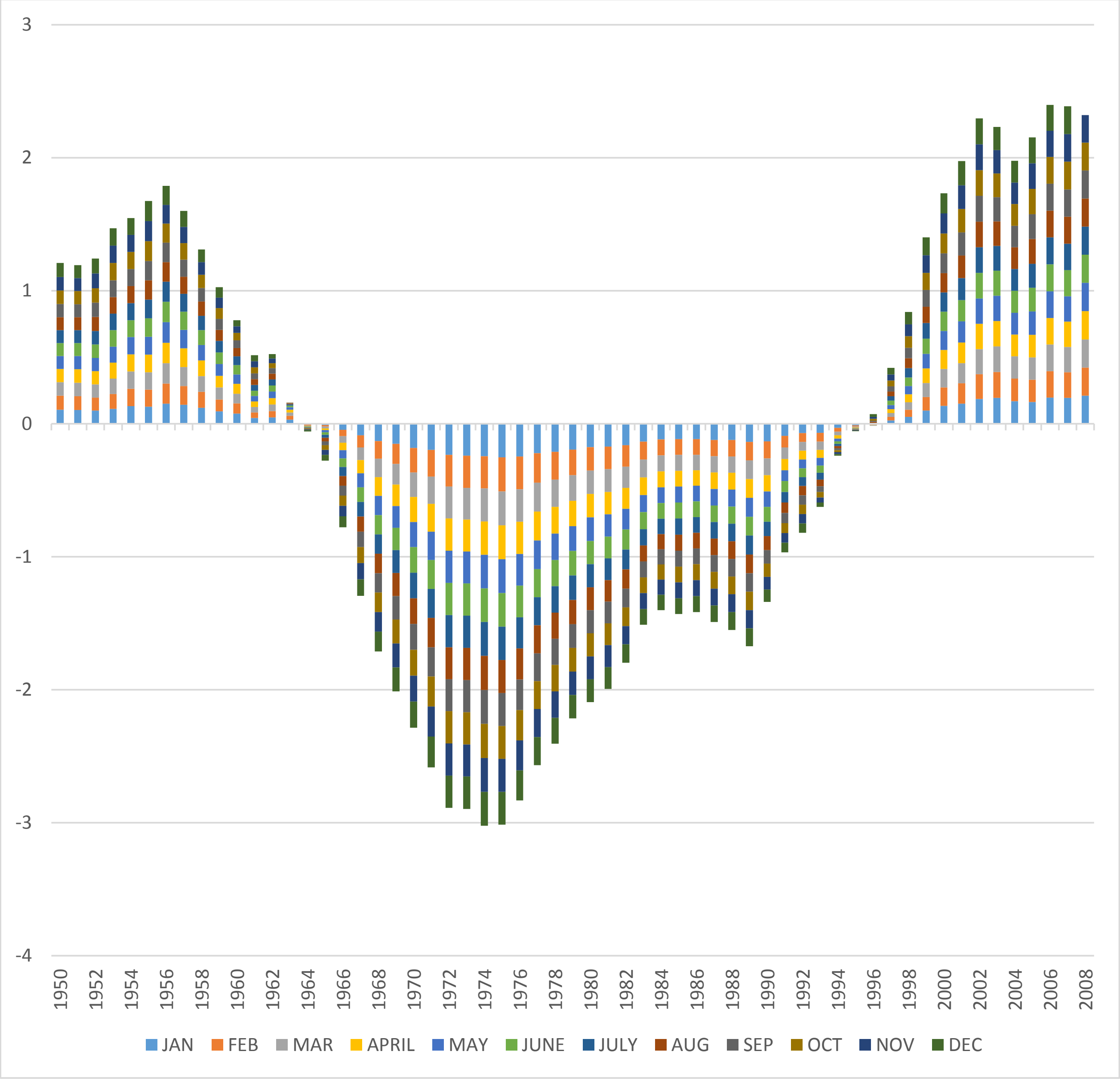

Figure 1.9 Atlantic Multidecdal Oscillation trends from 1950-2009 measured in departure from normal (C°) (NCDC 2013).

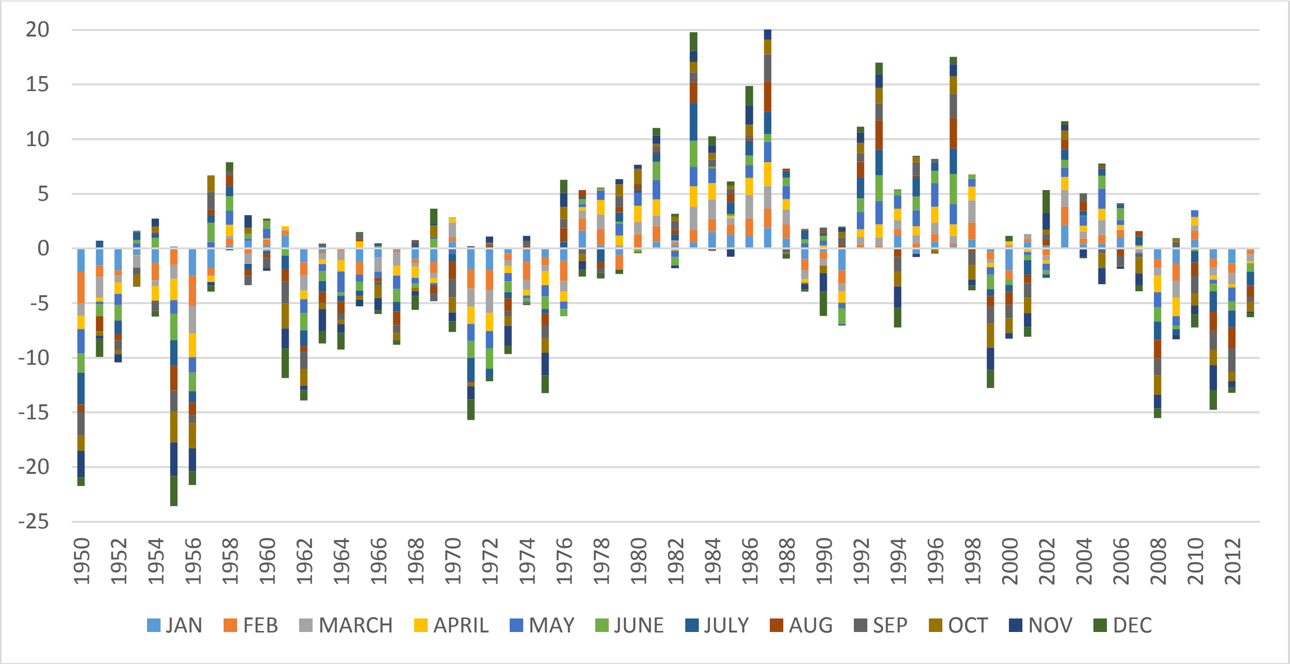

Figure 1.10 Pacific Decadal Oscillation averages from 1950-2009 measured in departure from normal (C°) (NCDC 2013)

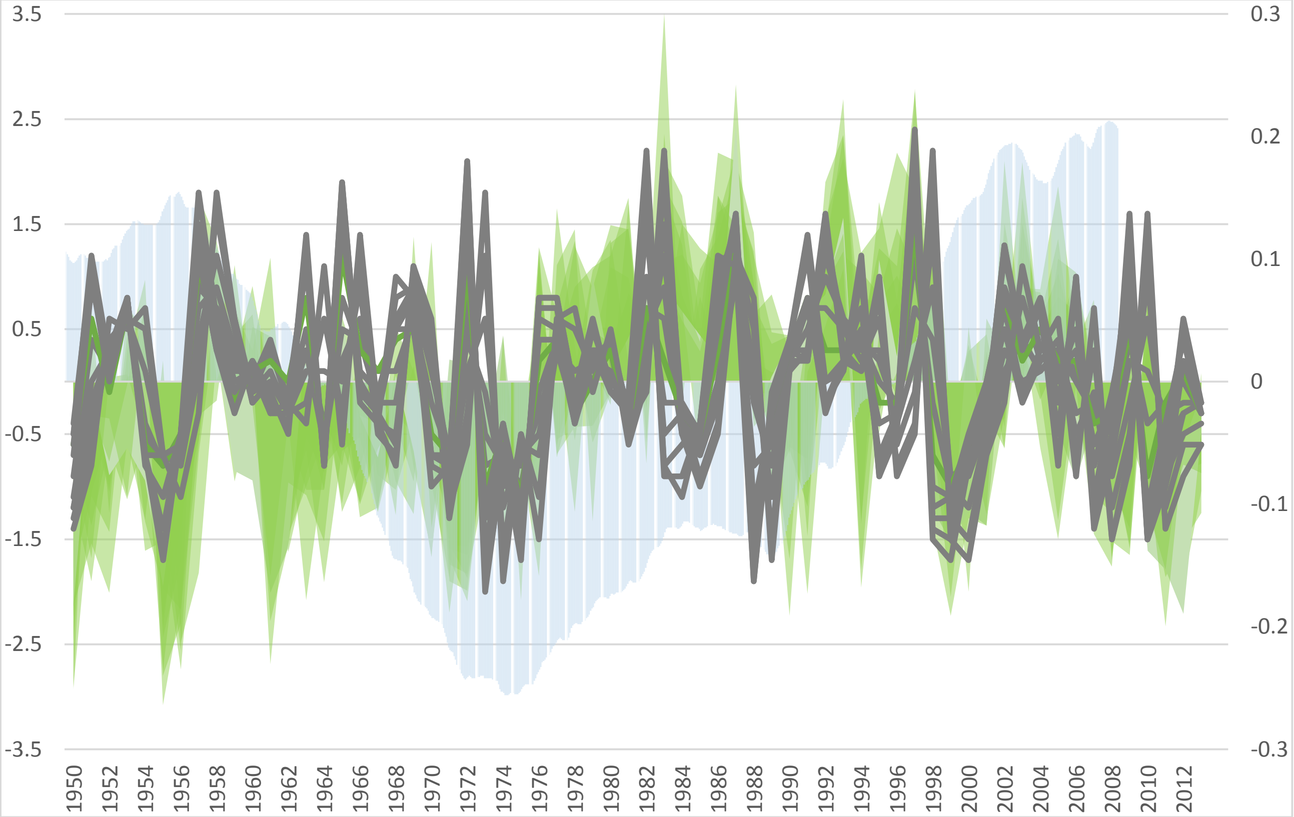

Figure 1.11 Composite of ENSO (gray line), AMO (green area), and PDO (blue) measured in departure from normal (C°) (NCDC 2013) 1950-2012.

2. LITERATURE REVIEW

2.1 Catastrophism, Gradualism, and Neo-Catastrophism

Catastrophism, the philosophy that rare, extreme events are the primary Earth-shaping force, disappeared from mainstream geography around 1830 CE, when Charles Lyell, among others, introduced the notion of gradualism in the wake of evolutionary biology and chemistry. Although Lyell never used the terms “gradualism” or “uniformitarianism” in his epic, discipline-defining 1830 book Principles of Geology (Baker 1998), he is often attributed as the founder of modern scientific methodology (Gould 2007). “The Present is Key to the Past” remains a staple of multiple disciplines, including geography, and has been consistently reinforced in literary works for more than 80 years (Marriner et al. 2010).

Gradualism dominated geographic thought for two centuries before it gave way for the rise of neo-catastrophism in the 1970s (Marriner et al. 2010). Neo-catastrophism takes on both theories and seeks to redefine evolutionary development: Neo-catastrophism is the theory that life (or Earth) is shaped by gradual changes, punctuated by extreme, rare events which change the course of design and establish a new equilibrium. Research on extreme events has increased significantly in the last 20 years, emulating the infamous global-warming climate hockey graph as it accompanies the rise of reported natural disasters. The broad appeal of disaster science, compounded with growing international awareness of climate change, has piqued the interest of scientists, the media, and the general public (Hecht 2009). Catastrophism requires retroductively generating a hypothesis, which complicates the quantification and validity of relevant research (Baker 1998). The role of the rare event in Earth’s history remains un-quantified, despite the dozens of papers published on the topic since 1990, limiting serious debate on geology to the realm of philosophy.

For more than 130 years, catastrophism had been labeled as “creation dichotomy,” a doctrine twisting scientific evidence solely for religious indoctrination and contradictory to 200 years of evolutionary and genetic research. Thus, the resurgence of catastrophism anew was not well-received in many fields. Scott (2007) criticizes the theory, claiming that neo-catastrophism, or punctuated equilibrium, is “a paradox, deeply superficial.” Bazerman (1993) called neo-catastrophism a “simplification” and “reductionist” approach to science, going as far as to call Stephen Jay Gould, an early enthusiast for neo-catastrophism, “willingly blinded.”

Gould’s approach to retroductive reasoning echoes earlier devotees of neo-catastrophism, like Nikolay Shatskiy, who first coined the term in 1950 (Pushcharovskiy 1986). Candid, almost poetic, the idea of neo-catastrophism caught fire across the discipline with Gould’s *Wonderful Life* (Gould 1990), despite the harsh criticism it received upon its release. Although Gould’s influence on the neo-catastrophic revolution was profound, he limited his research to tectonics with simple mathematical analysis.

Coastal communities need to know what forces shape their beaches and how those forces have been changing in recent years in order to make plans to adapt or retreat. If catastrophic events are more influential than currently believed, then emergency managers, city planners, and local governments should adjust their building codes and zoning. If those events are fleeting, leaving only small scars behind in the sand, then long-term plans need not focus on singular events, such as thunderstorms.

2.2 Geomorphological History

During the last glacial maximum (LGM; 18 ka (18,000 years)), eustatic sea level was at least 127 m lower than today (Blum et al. 2003).Vast networks of rivers were carved into the glacial seafloor of the northern Gulf of Mexico, creating valleys and shoals (Morton 2008). The shallow basin that built the Mississippi-Alabama system was formed during multiple periods of valley filling and reworking as fine-grained sediments were carried down various rivers from Appalachia to the Tombigbee River and ultimately into Mobile Bay (Bentley et al. 2000a). Tidal range is low within this island system, 0.4 m in summer and 0.6 m in winter, averaging less than 0.5 m throughout its daily highs and lows (Knowles and Rosati 1989). Tidal currents account for 50% of flow variance in the system (Byrnes et al. 2013). The island system experienced multiple submergence episodes during the last 6,000 years (Otvos 1979). While no evidence has been discovered recognizing laterally-forming island chains predating the Holocene in the study area, the reworking of fine sediments would stir the basin several meters into the seafloor, making detection difficult (Otvos and Carter 2013).

Sea level is a key factor in the development and sustainability of barrier islands, so episodic changes during the mid-Holocene would have a significant impact on barrier island evolution. During the LGM, the area currently occupied by the Mississippi Sound may have been covered with grasslands and mixed deciduous forests with spruce and pine trees (Balsillie and Donoghue 2004). At the onset of the Holocene about 11 ka, fresh water coming from melting glaciers continued to flow down a vast network of rivers through Appalachia into the Gulf of Mexico (Blum et al. 2003). The waters flowing through Mobile Bay deposited fine sediments, mostly quartz. The melting and deposition process filled in basins as sea level rose and consumed large areas of land.

Sea level continued to rise as the North American and European ice sheets retreated and ocean temperatures rose, allowing sea level to settle near modern levels around 3 ka (Blum et al. 2003)

The pace of local sea level rise in the northern Gulf of Mexico throughout the Holocene is still being debated (Bird et al. 2010). One study suggests that sea level rise changed abruptly in the northern Gulf of Mexico several times throughout the Holocene (Stapor and Stone 2004) but others contest that sea level was more gradual, continual, and in step with eustatic rise (Curray 1959, Fairbridge 1961, Shepard 1963, Levermann et al. 2013). Several studies suggest a more stair-step sea level rise process as far back as 6 ka (Blum et al. 2003, Pirazzoli and Pluet 1991).

There is disagreement within the literature as to exactly when the Mississippi-Alabama barrier islands formed. The study of Twichell (2011) posited that the islands formed around 4.514 ka. The study of Otvos (2005) estimates the islands' origins between 5.2 and 4.0 ka. That author went further to estimate that Horn Island formed at 4.6 ka, Cat Island at 3.8 ka, and East Ship Island between 2.1 and 1.5 ka (Otvos 2005). Stapor and Stone (2004) estimated barrier development initiating around 4.1 to 3.9 ka. Saucier (1994) offered a range of 5.0 to 4.8 ka. Most of the literature dates the islands' first emergence after 6 ka during a more steady state in sea level rise occurring around 5 to 4 ka (Blum et al. 2003, Flocks and DeWitt 2009). Although the island system may have emerged during this time period, the islands have changed and moved so frequently that it is unlikely that any remnants of the current five islands would be detectable in any of the sediment records dating as far back as 4 ka (Otvos 1970).

The sediment grain size and composition show that the islands are still receiving the bulk of their sediment from upstream mountainous sources, specifically Appalachia. Samples of the beach step, mid-tide level, and foredune crests at 45 stations sampled by Cipriani and Stone (2001) reveal that more than 90% of the sediment making up the barrier island system is quartz sand, with traces of carbonates and heavy minerals, defined by a distinctive tourmaline-kyanite array of heavy metals. The foredunes presented the most diverse range of composition, varying from 50–100% quartz sand with heavy minerals making up to 50% of the material (Cipriani and Stone 2001).

The minerals found in the foredunes include hornblende, ilmenite, kyanite, hematite, staurolite, and tourmaline – the high iron content of which indicates transport from mountainous areas. For example, ilmenite usually accompanies igneous rocks typically found in mountainous, high-iron areas. Hermatite is an iron oxide, also found in the Appalachia area. Staurolite is the official state mineral of Georgia and it is found in Virginia and Minnesota. According to Cipriani and Stone (2001), the texture of the heavy minerals ranges from 2.25 phi and 3.0 phi (fine sand). Heavy minerals were always finer than quartz grains, suggesting further wearing than the coarser quarts. Step sediments had a mean grain size range of 0.71 phi to 1.87 phi, lying in the coarse sand and medium sand classes (Cipriani and Stone 2001). On the beach face and mid-tide, sediments ranged from 1.347 phi to 2.07 phi, lying in the medium sand range. Foredune sediments have mean grain sizes ranging from 1.508 phi to 2.266 phi, lying in medium and fine sand range.

Multiple dredging and navigation projects during the last century deepened the Mississippi Sound channels, causing sediment sinks to form and disrupt littoral drift along the system, resulting in reduced deposition (Otvos and Carter 2013). The Mobile Bay Entrance Channel was deepened by 3.6 m from 1902 to 1986 (Morton 2007) and dredging in a channel near Horn Island from 1965 to 2005 removed an annual volume of 0.28 km^3 (Rosati et al. 2007). The U.S. Army Corps of Engineers created a dredge-spoil repository in the 1970s, which received more dredge material than the entire littoral drift volume of PBI over the same time period, creating what is now called Sand Island to its western flank (Stone et al. 2004). With sediment deprivation within the system due partly to dredging, sediment reworking following storms has been a primary source of new beach area in the last 40 years (Otvos and Carter 2013).

2.3 Oral and Modern History

The first documented encounter of humans with Ship Island dates back to 1686 when a Spanish fleet chartered the coastline in search of a French colony that had been destroyed in a violent storm years prior (Bearss 1984). The Spanish fleet encountered a violent storm itself and embarked for Veracruz, but documented the island chain in its ship log before moving on (Marsh 2013). The first settlement on Ship Island would come 13 years later in 1699. The settlement provided “a suitable harbor,” and “contained two small ponds which provided the necessary fresh water” (Iberville 2010). Two freshwater lagoons on the island, one each on both the eastern and western ends of the island, signal a period of low hurricane activity for some time before the French’s arrival (Bearss 1984).

The French troops hunted and killed all of the native geese on the island, and cleared its oyster reservoirs in a matter of weeks, foreshadowing three centuries of human degradation on the island (Iberville 2010). The men also documented that “on neither Ship nor Cat Islands did they see any sign that man had ever been there” (Iberville 2010). The French claimed the island and named it Surgeres. Once Pierre Le Moyne d'Iberville, known as Iberville, and his troops created a stronghold on Surgeres, and having not found a suitable place for a colony along the Mississippi River, the settlement moved to Ocean Springs, where Iberville met with friendly Biloxi natives and established a French colony (Bearss 1984). In August 1701, however, a strong hurricane caused considerable damage on Surgeres, with Iberville’s colony declaring the island “partially destroyed,” along with its two lagoons, which turned brackish and undrinkable (Iberville 2010). After a fateful hurricane season, Iberville renamed the island “Ship Island,” for he no longer saw it as an island paradise but rather a practical shipping port for the French (Bearss 1984). The island would be surrendered to Spain in the 1783 Treaty of Paris. The British took over and occupied Ship Island building up to the War of 1812, where they organized an attack on New Orleans, before eventually retreating and surrendering the island back to the Americans (GINS 2013).

The island remained in obscurity between the War of 1812 and the mid-1850s, serving only as a port and boat-anchor for large vessels moving into the Mississippi Sound (Marsh 2013). The U.S. government began nationwide fortification of its islands in 1858, but a series of tropical storms delayed construction (GINS 2013). In January 1861, soon after Mississippi succeeded from the Union, a troupe of Confederate soldiers took siege of Ship Island and its skeleton fort, which was subsequently razed (Hollandsworth 2014). The Confederates turned their gaze toward Mobile, however, and left the island unoccupied long enough for Union troops to move in and claim the land (Sherman 1908).

In late 1861, on the heels of a major loss at Bull Run for the Union, Major General Benjamin F. Butler sent the 9th Connecticut, the 26th Massachusetts, and the 4th Massachusetts to Ship Island in hopes of organizing an attack on Mobile or New Orleans (Butler 1892). When Butler’s army arrived to the island they had the area surveyed for construction locations. The army recorded an area of approximately 2 km from west to east. The island would have been one large island similar in shape to PBI today (Butler 1892).

At one point more than 15,000 union troops were housed on the island, preparing for an assault on New Orleans in 1862 (Butler 1892). Fort Massachusetts, which would not be completed until 1868, was used a prison and detention center for civilian detainees from New Orleans and for Union soldiers convicted of serious crimes (Bearss 1984). As the Civil War progressed, Confederate soldiers were detained in numbers as high as 3,000 in 1865 (Hollandsworth 2014). A letter sent from Captain John William DeForest on March 8, 1862, described Ship Island as a low stretch of sand, "almost white as snow," with no vegetation. DeForest wrote, "Here we are, at seven in the morning, dropping anchor within a mile or two of Ship Island. The water is smooth, the sky grey and lowering, the air damp but not cold" (DeForest 1946). Another solider, Private James F. Stoddard, described the island in a letter in April 1862: "the sand drifts like snow – it filled my eyes and ears full" (Hollandsworth 2014). The extra-fine white sand observed by soldiers during this time would later become courser, darker and imported.

Evidence of breaching dates back to the Civil War, with Lieutenant George G. Smith describing the would-be Camille Cut in detail in 1862: "On reaching the center of the island we found the water breaching over for about a mile, and this we waded" (Smith 1906). Smith also recorded the vegetation and marine life of the area, documenting the presence of fruit and palm trees, porpoises, and even alligators. "An alligator had been imprudent enough to show himself in a small pond of fresh water, and several officers and soldiers were watching for him with guns, but he was too cunning for them and they did not get him" (Smith 1906). While some soldiers described a complete lack of vegetation less sparse seagrass, Smith was describing trees and fruit. It is possible that troop stations on opposite ends of the island experienced different kinds of vegetation (Smith 1906). The vegetation cover would quickly change, however, as Union soldiers began farming on the island, germinating blackberry seeds, among others, to feed the soldiers in the summer months (Hollandsworth 2014).

Others wrote of the intense heat and heavy rain spells they experienced during their time on the island (Sherman 1908). Complaints of the climate were frequent, especially among Union soldiers unaccustomed to the Deep South (GINS 2013). Violent thunder and lightning storms killed soldiers camped on the island, who had no shelter when they first arrived. From James C. Biddle: “I found out this morning that the Guard Tent of the 31st Mass. Regt. Had been struck by lightning. It is only about 200 feet from our tent. Three men were killed and some 13 stunned” (Hollandsworth 2014).

Conditions on the island were by all accounts deplorable. From the Union Sanitary Commission:

> The wretched condition of Ship Island, a barren, desolate sand-spit, left free for the most part to alligators and such reptiles as abound in the swamps and lagoons of that region; the painful and variable climate; the sufferings of the men from diarrhea, influenza, and rheumatism; the badness of the food, which was of salt meat (no fresh meat being issued); the badness of the water, and the wretched system of cooking, made the presence of the Sanitary Commission not undesirable (Wormley 1863).

Men who lived on the island for prolonged periods of time went blind from prolonged exposure to the burning sun, coming from the sky above and from the sand below (Bearss 1984). Attempts to create burial grounds resulted in bodies being regularly exhumed and deposited along the beach by erosion and strong winds (GINS 2013). After the Civil War, the island was abandoned and remained relatively empty for fifty years (Hollandsworth 2014).

Since the Civil War, changes across the island chain have been well-documented (GINS 2013). Lighthouse keepers on the island from 1877 into the 1940s recorded every thunderstorm and cyclone that crossed its path, routinely surveyed the land, and oversaw construction of lighthouses and other structures (GINS 2013). Severe hurricanes in 1717, 1722, 1846, 1855, 1860, 1893, 1906, 1915, and 1947 all caused significant damage on the island chain (Marsh 2013). A report of severe storms details the impact of previous storms (GINS 2013):

> 1893, 85mph Oct 2nd from the S.W over 1,000 in Mississippi killed bodies washed ashore up to 1 month after landfall
> 1901 Aug 15th 90mph from the SSW
> 1906 Sept 27th ,a 130mph hurricane hits from the SSE. Quarantine station on Ship Island

> was devastated and lives lost. The storm ate one mile off east end of Horn Island, swallowing lighthouse and drowning keeper.
> 1916 July 5th a 120 mph hurricane hits the area for 16hrs killing 10
> 1926 Sept 20th a weakening cat 2 with 110 mph winds reached Gulfport with a calm eye for 10 min press 29.08 from the ESE

A sixth island, the Isle of Caprice ("The Island that Was"), was listed as a military reservation in the 1800s and was the subject of Native American tales about an island that would pop up and then sink again (Marsh 2013). It was located between Horn Island and ESI, first appearing in the mid-1800s, disappearing in 1859, reappearing in 1890, and completely disappeared by 1930, destroyed by a large hurricane (GINS 2013). The island never resurfaced (Marsh 2013). The history of this small island, often referred to as Dog Island because of a lone dog washed ashore during a particularly violent storm, could be foreshadowing the fate of other islands in the system today.

During the entire written record of the island system, westward translocation and erosion were slow, gradual processes driven primarily by littoral drift and sediment starving until the 20th century (Bentley et al. 2000b). Hurricanes in 1916 and 1948 created large overwash terraces and Hurricanes Ethel (1960) and Camille (1969) changed the shape and rate of erosion on each of the islands (Morton 2010). After Hurricane Camille struck the islands in 1969, the shape and rate of westward translocation decreased. Dams and channel dredging picked up during this time, adding to sediment deprivation (Byrnes et al. 2013). Hurricane Georges (1998) made landfall as a strong Category 2 hurricane and washed away a one-mile stretch of ESI (Schmid 2000).

From the time Georges made landfall through the 2005 hurricane season, all of the islands experienced an increased rate of variability in surface area. ESI and WSI were completely submerged for three days when Hurricane Katrina (2005) struck the Gulf Coast. When the islands resurfaced, WSI lost nearly a quarter of its surface area and ESI lost half of its surface area

(Hermann et al. 2007). Hurricane Rita (2005) hit weeks later, halting the recovery of the islands temporarily. The 2005 hurricane season left each of the islands in the system less than half their 2004 sizes. The island system is in a state of overall decline, with an overall 48% decrease in all Mississippi Sound barrier islands since 1948, which could ultimately lead to disappearance of the islands altogether by 2040 if current trends continue (Otvos and Carter 2008).

Otvos and Carter (2013) concluded that the 160-year history of the island chain reveals losses ranging from 26% to 53%. According to the study, PBI lost half of its area since 1848 and 37% percent after 1950 (Otvos and Carter 2013). Byrnes et al. (1991) determined PBI to be 614 ha in 1972 and 537 ha in 1986. This would make the island 39% smaller than it was in 1972 and 34% smaller than its 1986 area. The current study finds that PBI is 34% smaller than its 1984-1985 surface area, and estimates of PBI's 1972 area suggest it is 38% smaller than it was in 1972-1973, concurrent with the results of Byrnes et al. However, Byrnes at al. (1991) also determined that Ship Island (West and East combined) was approximately 411 ha in 1972 – 30 ha smaller than this study's finding of Ship Island for 1972 (442 ha), so major discrepancies exist between the two studies concerning what type of imagery was used and what time of year that imagery was taken.

Using data from Byrnes et al. (1991), Otvos and Carter (2013) determined that Ship Island lost 57.7% of its 1848 surface area – 32.8% of which occurred in the last 60 years. Flocks and DeWitt (2009) determined that Ship Island has lost 64% of its mid-1800s surface area. The current study finds that Ship Island has lost 25% of its 1972-1973 surface area. According to the combined data of both studies, PBI would have been 808-835 ha in 1848, making the island about 53% smaller at the time of the current study. Ship Island would have been around 600 ha – making it 49% smaller than its 1848 area. A study by Morton (2008) concluded that PBI lost 52% of its area and Ship Island lost 60% from 1848-2007. While there a minor discrepancies between the five studies (Byrnes et al. (1991), Morton (2008), Flocks and DeWitt (2009), Otvos and Carter (2013), and the present study), all show relatively the same degree of change. Each agrees, however, that the future of the islands is in dire jeopardy. According to Byrnes et al. (2013), "East Ship (erosion and overtopping) has been so frequent since 1969 that the island appears in danger of complete degradation within the next 10-20 years." In another study, Rucker and Snowden (1990) found "The demise of the Isle of Caprice and Dog Keys shoals provides historical evidence of total island destruction."

2.4 Climate Change and Island Impacts

Average annual temperatures during the last century across the U.S. Southeast cycled between warm and cool periods, with a warm peak occurring during the 1930s and 40s followed by a cool period in the 60s and 70s, and warming again from 1970 to today by an average of 1.2 C°, with more warming on average during summer months (National Climate Assessment (NCA) 2009). The numbers of days above 35°C and nights above 24°C have increased, and extremely cold days have decreased since 1970 (Kunkel et al. 2012). Scientists project a 2 to 5.5 C° rise in winter lows and 2 to 4 C° rise in summer highs in Louisiana by 2100 (Union of Concerned Scientists (UCS) 2013). This accompanies a regional temperature increase of 2.2 to 4.4 C°, with projected increases for landlocked areas 1 to 2 C° higher than coastal areas (NCA 2013). The July heat index, a measure combining temperature and humidity, could rise by 5.5 to 13 C°. The freeze line is also likely to move northward, meaning warmer winters throughout the state (UCS 2013).

Mississippi's average annual precipitation has increased slightly during the last 100 years, but the most significant observed change has been how the area gets rain (NCA 2013). More intense downpours in shorter time periods are becoming more frequent, meaning more flash flooding and infrastructure damage, and longer periods of drought between downpours (NCA

2009). Observed seasonal changes in precipitation show much drier spring and summer months, slightly drier winter months, and an increase in precipitation in the fall (NCA 2013).

Though thunderstorms are familiar and seemingly non-threatening, severe thunderstorms can lead to dangerous supercells, derechos, and tornadoes (NASA 2013). One study found that a doubling of greenhouse gases in the atmosphere would significantly increase the number of days that severe thunderstorms could occur in the southern and eastern United States (Brooks 2013). Climate model simulations suggest that on average, as the surface temperature and moisture increases the conditions for thunderstorms become more frequent (Del Genio 2007). Climate change decreases the temperature difference between the poles and the equator (Archer 2007). This may lead to a decrease in vertical wind shear, which is a major factor determining what type of severe weather occurs. These expectations are supported by a majority of the climate model simulations that have considered the variables (NASA 2013).

Severe thunderstorms are much more likely to form in environments with large values of convective available potential energy (CAPE) and deep-tropospheric wind shear. (Trapp 2007). Climate model simulations suggest that CAPE will increase in the future and the wind shear will decrease (NOAA 2013). Detailed analysis has suggested that the CAPE change will lead to more frequent environments favorable for severe thunderstorms (Brooks 2013).

When more heat is pumped into the marine system, warming up the atmosphere and the ocean, the venting associated with tropical cyclones increases (Christopherson 2009). As global temperatures increase, more venting occurs (Archer 2009). High sea surface temperatures (SST) lead to the evaporation of moisture, which provides fuel for the storm. Then it gives up the latent heat: that is what powers the storm. Together they provide for stronger storms (Emanuel 2007).

The potential intensity of hurricanes, a measure of the upper limit of a storm's strength, has increased by 10% since 1970 (McQuaid 2012). Both the average duration and the top wind speed of storms have also increased, the latter by 25% (NCA 2009). Recent studies of the post-1970 period show clearly that the destructive power of tropical cyclones has increased by 70% in the Atlantic and Pacific, owing to increases in intensity and duration (Emanuel 2013). Another study revealed that the global percentage of Category 4 and 5 hurricanes has increased during the past 30 years, again correlating with the rise in sea surface temperatures in the tropical cyclone generation regions (Emanuel 2005).

A 2005 study that examined hurricane impacts from 1900 to 2005 found that Category 4 and 5 storms accounted for only 6% of U.S. landfalls, but caused 48% of all hurricane damage (Emanuel 2005). Using this study as a starting point, and accounting for the projected mix of bigger storms and fewer smaller ones, NOAA projects that by 2100, the overall destructive potential of hurricanes may increase by 30%. Anthropogenic warming by the end of the 21st century will also likely cause hurricanes to have substantially higher rainfall rates than present-day hurricanes, with a projected increase of about 20% for rainfall rates averaged within about 100 km of the storm center (Emanuel 2005) .

Storm surge is typically responsible for the majority of deaths during hurricanes, and also usually causes the most destruction: Katrina killed more than 1,800 people and caused $125 billion in damage, mostly from the storm surge which reached as high as 6 m in southeast Louisiana and 8.5 m in parts of Mississippi (NCA 2009). The frequency of extreme storm surges is projected to increase by as much as 10 times in coming decades because of warming temperatures (Grinsted 2012). Anthropogenic warming by the end of the 21st century will also likely cause hurricanes to have substantially higher rainfall rates than present-day hurricanes, with a model-projected increase of about 20% for rainfall rates averaged within about 100 km of the storm center (UCAR 2013). Sea level rise, another product of climate change, will contribute to higher, more dangerous hurricane storm surges (NASA 2013).

Observations show that the world's oceans are already warming at depths greater than 457 m (IPCC 2013). The SST in the critical region for hurricanes is increasing. As this warming occurs, the oceans expand and raise sea levels (Archer 2009). Melting land ice also raises sea level, currently at a rate of 3.8 cm over the past 12 years (NCA 2009). Rising seas means that storm surges ride on a higher base level, turning even relatively minor storms into more flood events, thereby increasing storm damage along coasts (NCA 2009). By definition, higher seas mean higher storm surges. This means that storms that might once not have caused a problem are getting more dangerous. And huge storms, whether amplified by global warming or not, can go from destructive to catastrophic (NCA 2009). Grinsted et al. (2009) found that the number of moderately large storm surge events have been increasing since 1923, and that Katrina-magnitude events are two times more frequent in warm years. The danger is compounded by the fact that most coastal fortifications were built when sea levels were lower, on the assumption that conditions would not change.

Global sea level has risen about 20 cm during the last 100 years (IPCC 2013). But sea level rise at Grand Isle, Louisiana, averages 91 cm in 100 years - about four times the global average and one of the fastest rising levels in the world. Sea level will increase at a faster rate over the coming century (NOAA 2013). By 2100, ocean levels around Louisiana could be 60–120 cm higher than today, based on a continued average subsidence rate of 20–78 cm per century and a mid-range sea-level rise scenario (Osborn 2013). Even a relatively small vertical rise in sea level (up to 30 cm) can move the shoreline inland by a substantial distance (several meters) along low-lying, flat coastal areas (NCA 2009). Ongoing changes in climate will likely increase the rapid extremes the area has observed in the past. Rising seas threaten the system more than any other symptom of global warming (Archer 2009). Continued warming must be considered when assessing damage across the system and projecting future change.

‘

3. METHODS

This study reveals changes in surface area from 1972 – 2014 on WSI, ESI, PBI, and Sand Islands using remotely sensed data obtained from the United States Geological Survey (USGS). More than 600 Landsat satellite images taken intermittently since 1972 serve as the base of the project, with additional data being incorporated as necessary. The average of 14 images per year provides a means for calculating rates of natural erosion and accretion processes (Figure 3.1). Data taken immediately before and after hurricanes, severe thunderstorms, and mid-latitude cyclones measure the effect of catastrophic events on shaping the islands independently of the effects of gradual processes. Years with frequent tropical cyclone activity typically have more images than non-active years. Data on sand dredging and island nourishment, obtained from GINS and Army Corps of Engineers, were calculated as anthropogenic influence and subtracted from the total accretion the islands have experienced in the study time frame.

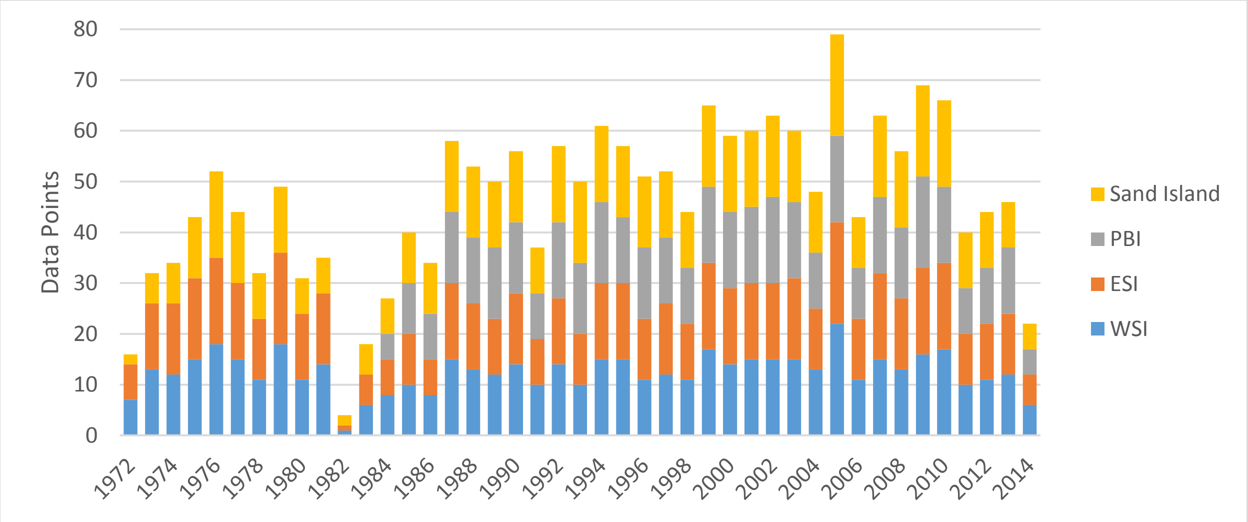

Figure 3.1 Number of data points taken from all images per year, per island. Temporal resolution increases depending on operating Landsat systems: Landsat 1: 1972-1978, Landsat 2: 1975-1981, Landsat 3: 1978-1983, Landsat 4: 1982-1993, Landsat 5: 1984-2011, Landsat 7: 1999-2003, Landsat 8: 2013-Present.

3.1 Image Selection

The Landsat imagery selected for this project met a predefined requirement: the entire island being measured had to be unobstructed by cloud cover, satellite spots, or other features that would limit visibility, without the need for image enhancement or correction. Data measurements may have included some but not other islands. For example, if cloud cover obstructed the view of WSI but not ESI, then a measurement was still recorded for ESI for that image date. This selection process resulted in a higher temporal resolution for WSI and ESI than PBI and Sand Island (Figure 3.2). Spatial and temporal resolution of the data and imagery improved as the time series progressed with multiple Landsat satellites concurrently in operation.

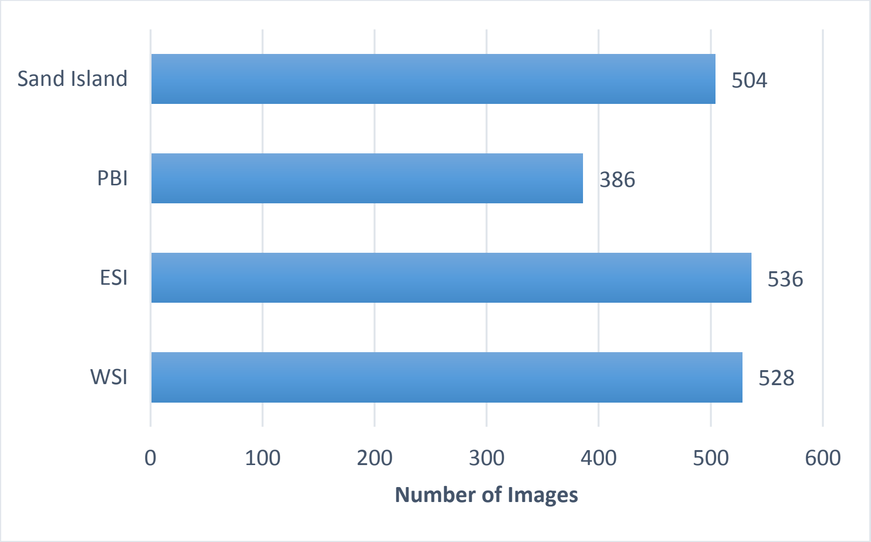

Figure 3.2 Number of images taken per island.

Spatial resolution varies between each Landsat sensor. Landsat 1 Multi-Spectral Scanner (MSS) (1972-1978) and Landsat 2 MSS (1975-1983) both had an 80 m ground resolution sensor. Landsat 3 MSS (1978-1983) had a 40 m ground resolution sensor. Landsat 4 MSS and Thermal Mapper (TM) (1982-1993) and Landsat 5 MSS and TM (1984-2013) had 30 m resolution sensors. Landsat 7 Enhanced Thermal Mapper (ETM+) (1999- present) also has a 30 m resolution. Landsat

8 Operational Land Imager (OLI) was launched in 2013 and has 15-30 m resolution, depending on the bands being used. Landsat 5 and Landsat 7 data make up more than 90% of the imagery used for measurements after 1984. The equal 30 m resolution between these two sensors allows them to be used interchangeably. Landsat 1 and 3 data make up most of the 1972-1983 data and have a lower spatial and temporal resolution. Landsat 2 imagery is used once during the study period. For these reasons, the data from the 1972-1983 time period should be considered less reliable than the data obtained following the Landsat 5 launch (1984 onward). However, comparisons of manual measurements of Landsat 1-4 data with studies by Waller and Malbrough (1976), Byrnes et al. (1991), and Otvos and Carter (2008) show similar approximate values with single dates (Table 3.1).

Table 3.1 suggests that the measurements by previous authors tend to represent the lowest areas during the specified time period. Depending on the time of the year in which a measurement is taken, particularly in relation to extreme events, the data could reflect more drastic changes than actually occurred. For example, a measurement taken in January 1973 may show an area twice the average size of the island for that year, and a measurement taken days after Katrina may show no island at all. The dates selected when determining island loss can make loss appear more or less severe because of natural seasonal fluctuations. Figure 3.3 shows the data by previous authors when graphed. The data create a smooth line with a slow and gradual decrease in area, unlike the current study which shows periods of rapid accretion and erosion, accented with abrupt losses caused by extreme events.

Table 3.1 Comparative results of Ship Island and Petit Bois Island surface area.

	Land Area, hectares (ha)			
Source:	**1973**	**1986**	**2004-05**	**Sept. 2005**
		Ship Island (both islands)		
Waller and Malbrough	385	-	-	-
Byrnes et al.	383	374	-	-
Otvos and Carter	-	-	408	204
Current Study:				
Closest period match:	395 (9/7/95)	374 (6/8/86)	398 (3/21/04)	207 (9/16/05)
Period High	476 (1/16/73)	407 (1/31/86)	425 (3/8/05)	209 (9/8/05)
Period Low	395 (9/7/73)	368 (6/24/86)	270 (6/12/05)	180 (10/2/05)
Period Average	440	389	336	207
		Petit Bois Island (PBI)		
Waller and Marlbrough	624	574	-	-
Byrnes et al.	-	537	-	-
Otvos and Carter	-	-	397	372
Current Study:				
Closest period match:	639 (5/3/73)	538 (9/28/86)	395 (6/12/05)	370 (9/1/05)
Period High	702 (11/17/73)	545 (1/31/86)	497 (12/18/04)	411 (9/16/05)
Period Low	639 (5/3/73)	510 (5/23/86)	390 (7/22/05)	370 (9/1/05)
Period Average	668	527	440	404

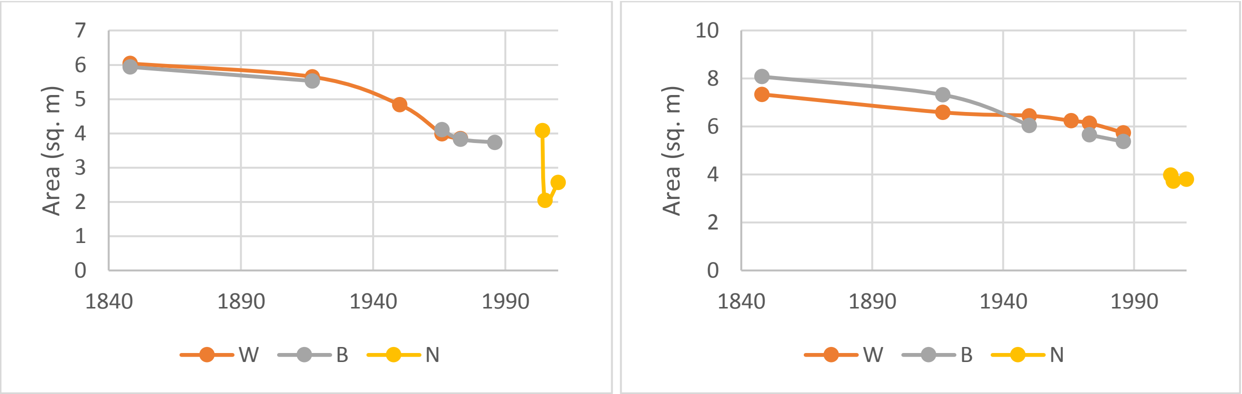

Figure 3.3 Ship Island area (left) and Petit Bois area (right) determined by Waller and Marlbrough (W), Byrnes et al. (B) and Otvos and Carter (N). The three studies show a smooth, gradual decline with few abrupt changes, unlike the current study which shows abrupt seasonal and annual changes.

3.2 Image Processing

All files were downloaded from EarthExlporer.USGS.gov as Level 1 Products in GEOTIFF format with reference data and metadata. All analysis took place in ERDAS Imagine software. ArcMap was used for the data visualization portion of this project. Landsat 1-4 imagery needed to be geocorrected for global positioning, meaning GPS points were tied to the images to increase accuracy of latitude and longitude coordinates. To geocorrect the imagery, ground control points, or "tie points," were collected on the islands using markers visible on the imagery. Examples of tie points include Fort Massachusetts, located on the northern end of WSI, the eastern and western-most points of each site, and visible intersections on the mainland. These tie points allow for exact positioning and more accurate calculations. Eighty tie-point coordinates were collected along the coastline. An accuracy assessment of this process, conducted in ErdasIMAGINE, averaged 87%, with Landsat 1 imagery averaging 92%, Landsat 3 imagery averaging 86%, and Landsat 4 imagery averaging 84%.

Landsat 1-4 MSS images used bands 4 (visible green), 5 (visible red), and 7 (near-infrared). The Landsat 4-5 TM and Landsat 7 ETM+ images were stacked using bands 1-5, and 7, adding three visible light bands (bands 1-3). The bands used have no effect on the spatial resolution, but do impact image clarity during analysis. This was considered during the measuring process. Using the toolset accompanying ERDAS Imagine, all measurements were done manually. After all of the measurements were collected, the data were examined to find outliers. Images showing an unaccounted for spike or drop in area were re-measured. If a large discrepancy between the first and second measurements appeared, the data were removed from the set and the image was discarded from analysis. This situation occurred three times out of more than 600 images.

To verify the accuracy of Landsat 7 measurements, the areas of WSI, ESI, and PBI were calculated using hand-held GPS units on the islands. The perimeter of each island was walked and the measurement was compared with the manual measurement of the Landsat 7 image taken the same day during the collection time. The Landsat 7 measurement was less than 0.04 hectares (ha) larger than field measurement taken the same day, which can be attributed to changes in tide during the measurement process. All calculations have been adjusted for a +/- 0.04 ha margin of error, a virtually insignificant figure compared to the relative size of each of the islands and the rates of change occurring on each.

3.3 Data Collection

Historical climate data were obtained from WeatherUnderground.com, a subsidiary of The Weather Channel. Each month of the record was examined to find spikes in wind speeds, drops in barometric pressure and total daily precipitation. A sudden change in any of these conditions can signal a severe weather event. After a date was determined to show spikes in any of these factors, hazard data could be identified using the FEMA disaster declaration search engine. If a change of more than 10 ha occurred on any island, the month in which the image data were taken was examined for these climate signals. Sea level data were obtained from the National Oceanographic and Atmospheric Administration (NOAA). Because tidal gauge data on Ship Island are fragmented and incomplete, data from Mobile, Alabama, are influenced by the rivers flowing out of Mobile Bay, and less than 20 years of data are available at Waveland, Mississippi, the comparisons between sea level and area used in this study were recorded at the Pensacola, Florida, station (station ID number 8729840). The station began recording in 1923 and has been the most consistent and reliable station along the northern Gulf Coast for more than 80 years.

3.4 Climatological Analysis

An island ecosystem depends heavily on the health of its marine and plant life, ocean currents, turbidity and wave action, fluent depositional patterns, and climatological factors, such as temperature, precipitation and humidity. Using the R Project for Statistical Computing, all of the data were analyzed for break points and linear regression using iterative searching and piecewise regression. A time series analysis using the Multivariate Auto-Regressive State-Space (MARSS) package, with Gaussian errors, found temporal patterns between the surface area and multiple climate datasets, outline in the results section of this thesis.

3.5 Statistical Analysis

The statistical techniques used in quantifying catastrophism on the study area allowed for analysis of the significance of catastrophic events and global climate mechanisms. For calculating the Pearson correlation between surface area and various climate factors (e.g. sea level, temperature, and precipitation), 20 Pearson correlation matrixes were created using the open-source software R Project for Statistical Computing, or simply R. Diagnostics, linear regression, break point analysis, time series analysis, generalized least squares, and linear and non-linear mixed effects models formulas were provided by various packages in R. Climate analysis included analysis using S3 and S4 functions for spatial and multi-site stochastic generation of daily time series of temperature and precipitation making use of vector autoregressive models.

Using the data obtained from the imagery, two equations were used to solve for the relative impacts of extreme events; the first calculated and singled out each variable according to its relative influence of surface area change by accounting for all amounts of change in absolute values; the second confirmed that all amounts equaled total surface area losses and additions as calculated by the data on the first and last image date (Table 3.2). The function developed to calculate relative surface area change (R) and total change (Δ) considered anthropogenic influences (An), accretion (Ac), catastrophic events (CE), and erosion (E). Total surface area change (Δ) included every input and output resulting in any negative or positive net difference in surface area, expressed in absolute numbers.

To start, all change observed on the island was calculated in absolute numbers. Then all of the sources of change were pulled out to evaluate relative impact. Example: Anthropogenic influences may have added 150 ha during the 40-year study period (An = 150). Catastrophic events may have accounted for 3500 ha of erosion (CE = 3500). The only two figures remaining are natural erosion (E) and accretion (Ac). The figures can be found using the equation below since erosion would be reflected in loss and accretion in gain. Using Δ, the impact of each individual source of change was determined. To determine the percentage of change caused by catastrophic events, CE (3500) was divided by Δ (7650) to determine that 45.7% of all change occurring on the island is a result of catastrophic events, making a strong case for neo-catastrophism in that hypothetical scenario:

Table 3.2 Equations for calculating the relative impacts on surface area.

$\mathbf{\Delta = An + Ac + CE + E \pm k}$ $\mathbf{7650 = 150 + Ac + 3500 + E \pm k}$
$\mathbf{R = 150 + 3000 - (3500 + 1000) \pm k}$ $\mathbf{R = -1350 \pm k}$
$\mathbf{R = Ac \pm An - (CE + E) \pm k =}$ $\mathbf{Surface\ Area = A_{1972} - A_{2013}}$

A second equation, the Relative Surface Area (R) equation, serves two purposes: first, to determine the total surface area loss between the first image (1972) and the final image (2014) of the research timeframe; second, to verify that all values calculated during the measuring and research process to determine total surface area change (Δ) are correct. The simplest way to calculate the difference in area is to subtract the total area of each island in the last image from that of the surface area taken in the first image to get: Surface Area = $A_{1972} – A_{2013}$.

3.6 Interpreting the Results

The time between when a storm made landfall and when the Landsat image was taken can affect the apparent magnitude of impact of a given storm. For example, if an image was taken on the day after a tropical storm struck the islands, the storm may appear to have had a larger impact than a Category 3 hurricane in which an image was taken a month after the storm hit. For this reason, the time between the images and the storms was included in the summary of each major hurricane. A severe winter storm or hurricane could disrupt the rate of growth, as well. So while a net loss may not occur between images, a stalling of natural growth in the order of magnitude similar to a hurricane may have occurred. Those figures were not calculated as part of catastrophic event damage. If there are multiple events between image dates, such as two hurricanes making landfall within a week of each other, the damage was attributed to both storms, as separating them with the available data is not possible.

Also not considered in this study are any changes in sediment availability caused by hurricanes or humans, including damming upstream and channel dredging. Sediment changes along the northern Gulf Coast have been largely due to a combination of damming and dredging and have had a considerable impact on the volume and direction of sediment in the area. Turbidity and wave action changes also affect sediment yield. However, these factors are outside the scope of this project, which focuses on the interaction of climate and coastal landforms and not suspended or deposited sedimentary processes. While overall changes in sediment volume on the system have previously been studied (Byrnes et al. 2009), how much of the sediment change can be attributed to a given cause across the study area and time period has yet to be determined. Considering the long-term impacts of each of these processes, the impact of catastrophic events is likely greater than reflected in the dataset.

Dune structure determines a large portion of how much overwash occurs on an island during a tropical cyclone – a high foredune blocks much of the storm surge from pushing sediment off the islands and into the bay. If the foredune is destroyed, more of the sand can be pushed inland. This theory can explain why hurricanes in 2005 created an increasing and cascading pattern of erosion – Hurricane Katrina destroyed the foredune, allowing Hurricane Rita to wash more of the area away – more even than Katrina did itself. While Katrina may have moved more sand in the 3-dimensional sense, Rita washed more of the islands on the northern and eastern edges into the surrounding ocean and bay. Rebuilding of the foredunes would provide a strong defense against storm surge in the future. Foredune building takes time, however, and unless multiple years pass without a significant hurricane, foredunes will have a difficult time building.

4. RESULTS AND DISCUSSION BY ISLAND

4.1 Overview

The changes experienced across the Mississippi-Alabama Barrier Island system from 1972-2014 can best be described as synchronous, yet highly variable, and generally escalating in intensity (Figure 4.1). Statistical analysis of the variance, correlation, covariance, linear regression, and breakpoints revealed distinct patterns that were observed for all islands across the system mostly in harmony with one another. Extreme events with noticeable impacts on the island system have increased in frequency and intensity over time and the ongoing natural and anthropogenic erosion has reduced one of the islands (ESI) to nearly half its 1972 size. The proportion of damage caused by extreme weather events like tropical cyclones, thunderstorms, and mid-latitude cyclones has increased over time and has eclipsed the total damage inflicted by all other causes.

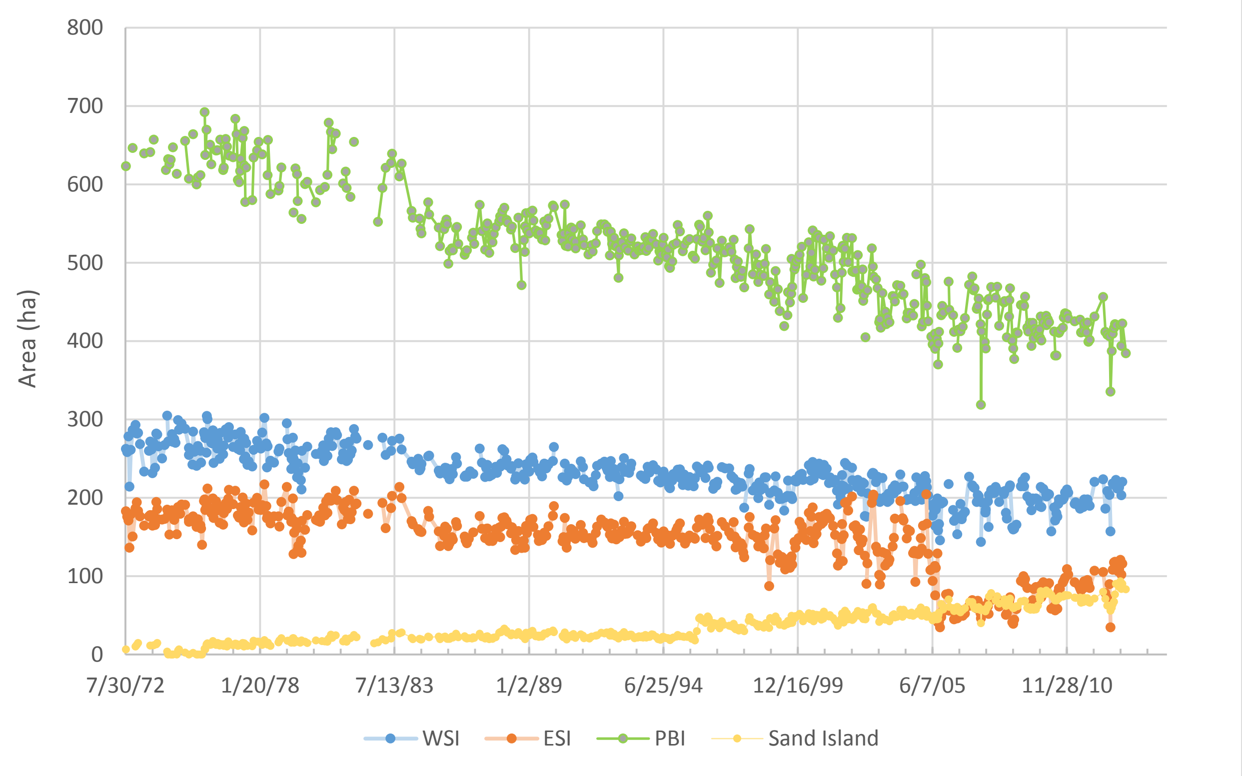

Figure 4.1 All island areas over time, measured in hectares (ha).

Each of the islands underwent significant transformations that can be divided into four time periods relative to rates of change and periods of growth and erosion. A break point analysis using piecewise regression revealed the same four distinct time periods across all four islands. The first period started in July 1972 and ended in December 1983. Because data for PBI do not start until 1984, PBI was excluded from analysis of this period. The second break occurred in 1998 following Hurricane Georges (September 1998) and lasted through August 2005. The third and final break occurred during the 2005 hurricane season and lasted through the end of the 2014 period of record. The timing of the 2005 break varied somewhat between islands, with WSI showing a break at the start of the 2005 hurricane season, and ESI and PBI showing the break following Hurricane Katrina. Sand Island did not follow these patterns as closely as the other islands and often experienced opposite growth and recession patterns superimposed on its rapid overall growth.

Table 4.1 Variability by island and by time period.

	Period I	**Period II**	**Period III**	**Period IV**
WSI	324.99	142.06	315.56	371.32
ESI	272.549	122	952.71	482.87
PBI	--	122.32	1510.78	726.46
Sand Island	42.14	49.02	27.61	88.45

Temporal variability in the islands’ area decreased from Period I to II, increased from Period II to III, and decreased again from Period III to IV for WSI, ESI, and PBI. Period II was the least-variable time during the study period, with each of the three larger islands experiencing similar variances (Table 4.1). Sand Island experienced the opposite patterns of variability, increasing from Period I to II, decreasing from Period II to III, and increasing from Period III to IV. This opposite pattern of growth, erosion, and variance on Sand Island appears throughout all of the results. PBI showed higher variability than all other islands for Periods III and IV. Variability during the most-recent period (IV) remained well-above the variance for Periods I and II, but less than the total variance for Period III. Although hurricane activity was much more frequent during the fourth period, overall variance in area was still lower, suggesting that extreme events may not be the sole driver of variance on the islands, even though hurricanes mark the start of both Periods III and IV.

Not surprisingly, sea level was negatively correlated with area for all islands throughout the entire time period, with the strongest correlations occurring on ESI, WSI, and PBI, and less so with Sand Island. Sea level likely caused the dramatic seasonal changes observed across the island chain during the time series, with R^2 values showing a negative Pearson correlation ranging from 0.441 for PBI during Period IV to 0.646 for ESI during Period III. Data from Pensacola and Dauphin Island show varying relationships between each of the islands and within time periods depending on which factor was used in analysis, including mean sea level, highest level, mean low sea level, etc. The strongest correlation between surface area and sea level for each island was -0.534 R^2 for WSI and -0.519 R^2 for PBI during Period II, and -0.646 R^2 for ESI and -0.411 R^2 for Sand Island during Period III (a negative R^2 value reflects a negative correlation).

Table 4.2 Summary of linear regression model considering sea level and time with area for west ship island during all four time periods.

	Estimate	**Std.Error**	**T-Value**	**Pr (Iti)**
Intercept	3.865^{02}	1.090^{01}	35.46	2.0^{-16}
Sea Level	-4.150^{-02}	3.993^{-03}	-10.39	2.0^{-16}
Time	-5.570^{-03}	1.512^{-04}	-36.83	2.0^{-16}
R^2: 0.7603	F-Statistic: 828.7	P-value: 2.2^{-16}		

A linear regression model of surface area on WSI with sea level and time resulted in a 0.7603 R^2, a 2.2^{-16} p-value and an F-statistic of 828.7 (Table 4.2). Highest sea level also correlated with change as a percentage of area over time along with extreme precipitation days: -0.189 R^2 and -0.173 R^2 on WSI, and -0.247 R^2 and -0.171 R^2 for highest sea level and extreme precipitation days, respectively. Both highest sea level and extreme precipitation days could be signaling extreme events (for example, storm surge and intense rainfall), which would increase the R^2 value. So while sea level data reflects the seasonal rise and fall of the ocean, it also reflects the intensity of extreme events.

Table 4.3 Pearson correlation analyses results table of each island with various factors during all study periods.

Factor	**WSI**	**ESI**	**PBI**	**SAND ISLAND**
Petit Bois Area	0.923	0.881	1	-0.791
West Ship Island Area	1	0.876	0.923	-0.648
East Ship Island Area	0.876	1	0.881	-0.756
Sea Level (Pensacola, Fla.)	-0.424	-0.419	-0.308	0.151
Time Series	-0.854	-0.818	-0.894	0.920
Days Per Month Above 32^{o}C	-0.142	-0.174	-0.281	0.132
Days Per Month With Min Temp Below 0^{o}C	0.157	0.116	0.031	0.225
Extreme Maximum Monthly Temperature	-0.232	-0.219	-0.279	-0.035
Extreme Minimum Monthly Temperature	-0.263	-0.213	-0.216	-0.094
Mean Monthly Temperature	-0.259	-0.219	-0.220	-0.064
Mean Minimum Temperature	-0.270	-0.215	-0.193	-0.093
Mean Maximum Temperature			-0.247	-0.033
Total Monthly Precipitation	-0.156	-0.031	-0.077	-0.034
Extreme Daily Precipitation	-0.169	-0.008	-0.020	-0.065

Period I started during a strong La Niña event which lasted through February 1976, began with two violent years of hurricanes and thunderstorms, occurred during the end-run of a global shift from a cool to warm Pacific Decadal Oscillation (PDO), and ended with moderate island growth highly correlated with a lowering of mean sea level (-0.715 R^2). Of the four time periods, Period I displayed the second-lowest variability (variance = 272 for ESI), though differences in the spatial resolution of Landsat 1-4 imagery may be inflating variability. Sand Island permanently breached the surface during this period (1975), having only intermittently penetrated the surface up to this point. Several significant tropical cyclones struck during this time period: Hurricane Dawn (1972), Tropical Storm Delia (1973), Hurricane Anita (1977), Hurricane Babe (1977), Hurricane Bob (1979), Tropical Storm Claudette (1979), and Hurricane Frederick (1979). Break-point analysis reflected a minor break within this period, occurring at the start of the 1979 hurricane season and at the start of the PDO warm phase. The break was reflected in the WSI and ESI analysis and only registered when sensitivity to rate changes was heightened. Because the break point was minor, it was not included as a major time period.

Period II starts with the launch of Landsat 5, a higher-resolution multispectral scanner than Landsat 1-4, and a period with generally consistent global temperatures and a decrease in Atlantic hurricane activity, shown in the low variability in surface area throughout the time period. Period II began in 1984 and continued up to the landfall of Hurricane Georges (September 1998). With few hurricanes and more-uniform data, variance decreased from 324 to 142 for WSI, and 272 to 122 for ESI. The only significant impact by a hurricane occurred in 1992 (Hurricane Andrew) with 20 ha of damage on WSI – barely making the mark of the 20 most-impactful storms during the study period. This period was defined by seasonal variability due to sea level change (-0.543 for WSI, -0.61 for ESI, -0.536 for PBI, and -0.341 for Sand Island) and an overall decrease in area over time presumably due to rising sea levels and sediment depletion, though the net sediment deposition during several years of this period was positive.

The third period, September 1998 to July 2005, showed an increase in variability marked by the start of several years of intense hurricanes. The islands began to destabilize, vegetation cover diminished, and ESI temporarily split into two smaller islands following the landfall of Hurricane Georges (1998). Four years after the beginning of Period III (2002), tropical cyclones

Bertha, Eduoard, Fay, Hanna, Isidore, and Lili together eroded 30-50 ha on each island. The 2002 hurricane season completely destroyed the third island that split from ESI during Hurricane Georges, leaving only the severed eastern half of ESI at about 45% of its pre-Georges area. Period III began as ENSO cycles shifted to a La Niña cool period from July 1998-February 2001. La Niña phases are associated with more active Atlantic hurricane activity, shown in the dramatic increase of accumulated cyclone energy from less than $50x10^4$ $knots^2$ in 1997 to 180 $x10^4$ $knots^2$ in 1998 (Emanuel 2005). Hurricane Georges triggered a high variability (1510 variance for PBI) period which would later be reduced by the near-total destruction of the islands caused by Hurricanes Katrina and Rita (2005).

The fourth period, August 2005 to March 2014, starts with the landfall of Hurricane Katrina, which immediately washed away 69% of ESI, 21% of WSI and 8% of PBI. Katrina resulted in a net gain of about 1 ha on Sand Island. After Hurricanes Katrina and Rita, ESI and WSI started their respective recovery periods, with an overall growth trend since the 2005 hurricane season with medium variability (371 for WSI, 482 for ESI, 726 for PBI, and 88 for Sand Island). Both WSI and PBI reached their pre-Katrina/Rita area levels within a year of the hurricane landfalls. ESI continued to grow, but as of this publication has not stabilized at pre-Katrina levels.

The 2008 hurricane season eroded more area overall than the 2005 season for WSI, PBI, and ESI, even though the 2008 hurricane season had fewer storms with overall lower intensity in terms of wind speed, storm surge, rainfall, and duration. Within three weeks, three tropical cyclones (Fay, Gustav, and Ike) made landfall on or near the study area, eroding 27% for WSI, 48% for ESI, 17% of PBI, and 17% of Sand Island. Hurricane Isaac (2012) erased much of the system's regrowth, eroding 24% of WSI, 62% of ESI, 18% of PBI, and 12% of Sand Island. Nourishment projects (2011-2012) on WSI and ESI added 600,000 cubic yards (about 45 ha) and helped accelerate the post-Isaac recovery, particularly on ESI which jumped from an area of 34 ha on September 11, 2012, to 108 ha on October 13, 2012. This observed increase on ESI occurred soon after the Isaac overwash and submergence receded, sea level was lowering, and nourishment projects resumed.

A total of 156 observed catastrophic events caused 54-59% of all change on the islands during the study period. Hurricanes, thunderstorms, and winter storms caused 26-37%, 11-13%, and 11-14% (respectively) of all change across the islands. Extreme weather events eroded a combined 380 ha of permanent surface area from the islands – equal to the entire area of PBI at the end of the study period. More than 20,000 ha of surface area was exchanged during the study period – enough surface area to cover the entire city of Biloxi twice. On top of seasonal variability due to sea level and various climate factors, storms pummeled the islands for four decades. The five most erosive events during the study period were Hurricanes Georges (1998), Katrina (2005), Barry (2007), Gustav (2008) and Isaac (2012). Together these five storms eroded 853 ha from the four islands. The 50 most erosive extreme events identified in the data eroded an accumulated 4400 ha of surface area.

WSI's surface area was 215 ha on the last image date of the study period, about 25% less than its 1972 area. ESI settled at around 110 ha at the end of the study period, about 39% less than its 1972 area. PBI continued to erode but stabilized at around 400 ha at the end of the study period, though its changes became more abrupt and intense during Period IV, leaving the island 38% smaller than its 1972-1973 area. WSI, ESI, and Sand Island all ended in accelerated growth periods, gaining sediment following a very quiet 2013 hurricane season, while PBI was still experienced an overall decline in surface area.

4.2 West Ship Island: Summary

Extreme weather events caused more than half of all the observed change on WSI from 1972-2014. The data show a total 6,536 ha of change throughout the entire time period, 3289 ha total loss and 3247 ha total gain (Figure 4.2). Of the 3,289 ha of loss, 2,645 ha have been attributed to catastrophic events (80.4% of all losses). Hurricanes caused at least 1,141 ha of loss (17.4% of all changes occurring during the time period, 34.6% of all losses, and 43% of all catastrophic event losses). Thunderstorms caused 809 ha loss and winter storms caused 695 ha of loss. Hurricanes caused significant change on the islands, including both growth and loss. Of the 3,247 ha of gain, 655 ha (19% of all gains) was attributed to hurricane reflex - the bounce-bank of surface area following submergence from a hurricane or movement of sand bars to shore. From the first image of the series to the last, the data show 42 ha of net loss, about 16% of the island's 1972-1973 surface area.

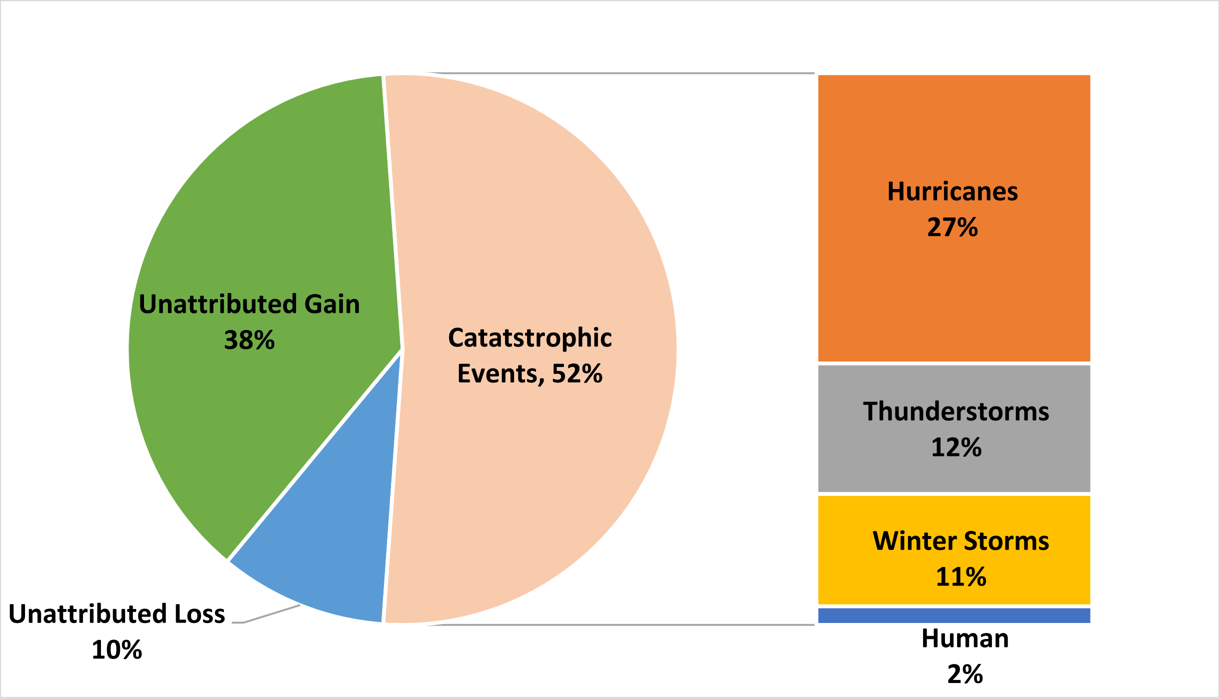

Figure 4.2 Causes of change on West Ship Island.

Four of the five most erosive events on WSI occurred during or after 2007: Tropical Storm Barry (2007), Hurricane Gustav (2008), thunderstorm (2010), and Hurricane Isaac (2012). Hurricane Katrina was the seventh-most impactful event overall, but may have initiated increased erosion, enabling storms post-2005 to be more erosive. The 15 most erosive events included eight hurricanes, three tropical storms, three thunderstorms, and one winter storm. Hurricane recovery slowed over time, with the WSI recovery period taking longer to recover as time progressed (Figure 4.3). Figure 4.3 shows the area of WSI across days relative to storm landfall. Within 60 days, WSI typically recovered most of its lost surface area, observed with Hurricanes Dawn, Andrew, Emily, and Eduoard. As the time series advances, hurricane recovery slows, as observed with Hurricanes Georges, Katrina, Gustav, and Bob, which all reach pre-storm area after 80 days. WSI often grew after 60 days had passed since hurricane landfall, observed by Hurricanes Dawn, Bob, Eduoard, Georges, and Andrew. However, Hurricanes Katrina and Gustav show only partial recovery and no growth.

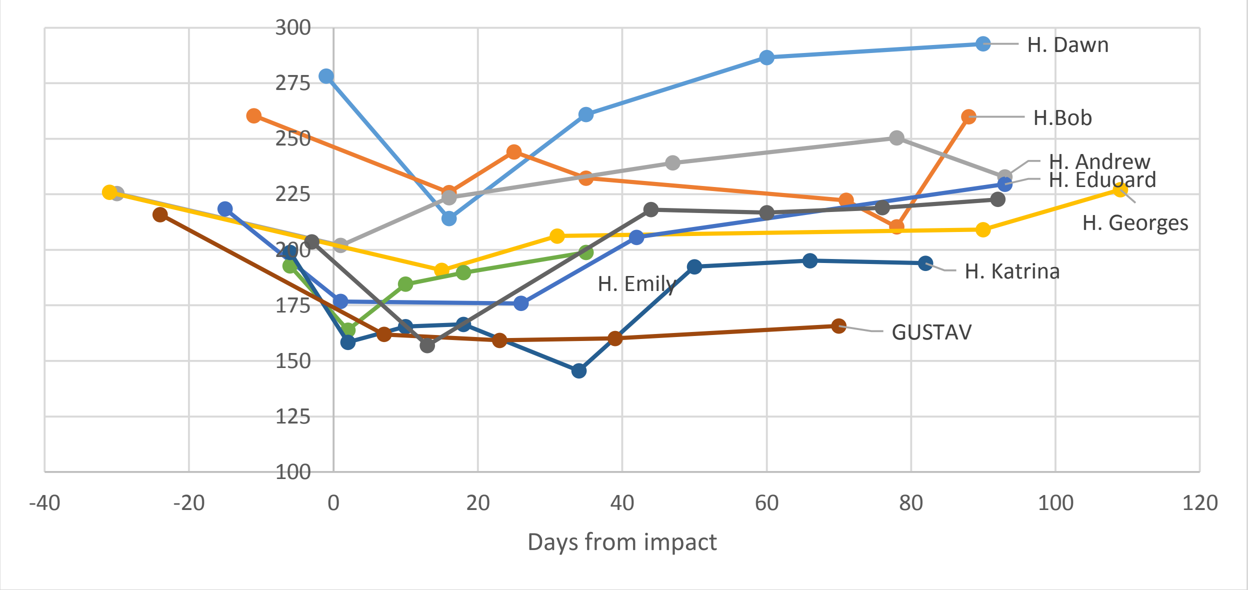

Figure 4.3 Hurricane recovery periods for West Ship Island. Stone et al. (2004) also found that large storms disrupt the island system “to the extent that post-storm recovery does not occur for several years” (Page 75).

Beach nourishment and dredging projects on WSI have also changed the rates of growth and loss. Each of the seven projects occurred either on the north beach near Fort Massachusetts or on the eastern spit of the island (Williams 2013). The projects added between 4 and 46 ha of area during periods lasting months to several years. Restoration projects can have a ripple effect on the islands, stalling erosion for a continued period of time even if the initial amount of area added was relatively small (e.g. 4 ha). The total surface area added through all of these projects was 115.9 ha, or about 2% of all change (Table 4.5).

Table 4.4 Nourishment projects added area to West Ship Island and East Ship Island.

year	cubic yards	approx. ha
1974	500000	38
1980	100000	7.6
1984	210000	16
1991	50000	4
1996	55000	4.3
2002	Unknown	n/a
2011-2012	600000	46
Total	**+1515000**	**+115 HA**

WSI’s decline has been stable and gradual compared to ESI and PBI, relative to its size and exposure to extreme climate events. WSI has been less impacted by hurricanes than ESI even though they are less than a kilometer apart and had previously been joined. Its shape, vegetation cover, and efforts to preserve the island may have resulted in slower rates of erosion. Limited range in variability compared to ESI and PBI and stronger correlations between sea level, precipitation, and temperature with surface area makes WSI less vulnerable to extreme events but more sensitive to large-scale climatic change. Its unique responsiveness to extreme rainfall events and higher minimum and maximum temperatures could allow it to be eroded at an accelerated rate compared to other barrier islands in the area.

4.2.a. West Ship Island: Period I

Hurricanes plagued the first two years of the study period on WSI: Subtropical storm Alpha struck on May 25, 1972, Hurricane Agnes on June 19, 1972, Hurricane Dawn on September 13, 1972, and Tropical Storm Delia on September 4, 1973. These four events eroded about 130 ha of area from WSI. In the winter months, the island typically grew to 290 ha, usually in December or January. Aside from the impacts of extreme events, the island shrank during spring between mid-March and early May before it started growing again in July. The island reached its maximum surface area for the entire study period on April 10, 1974 at 304 ha. The island grew above 300 ha only twice during the entire study period - in April 1974 and in March 1978.

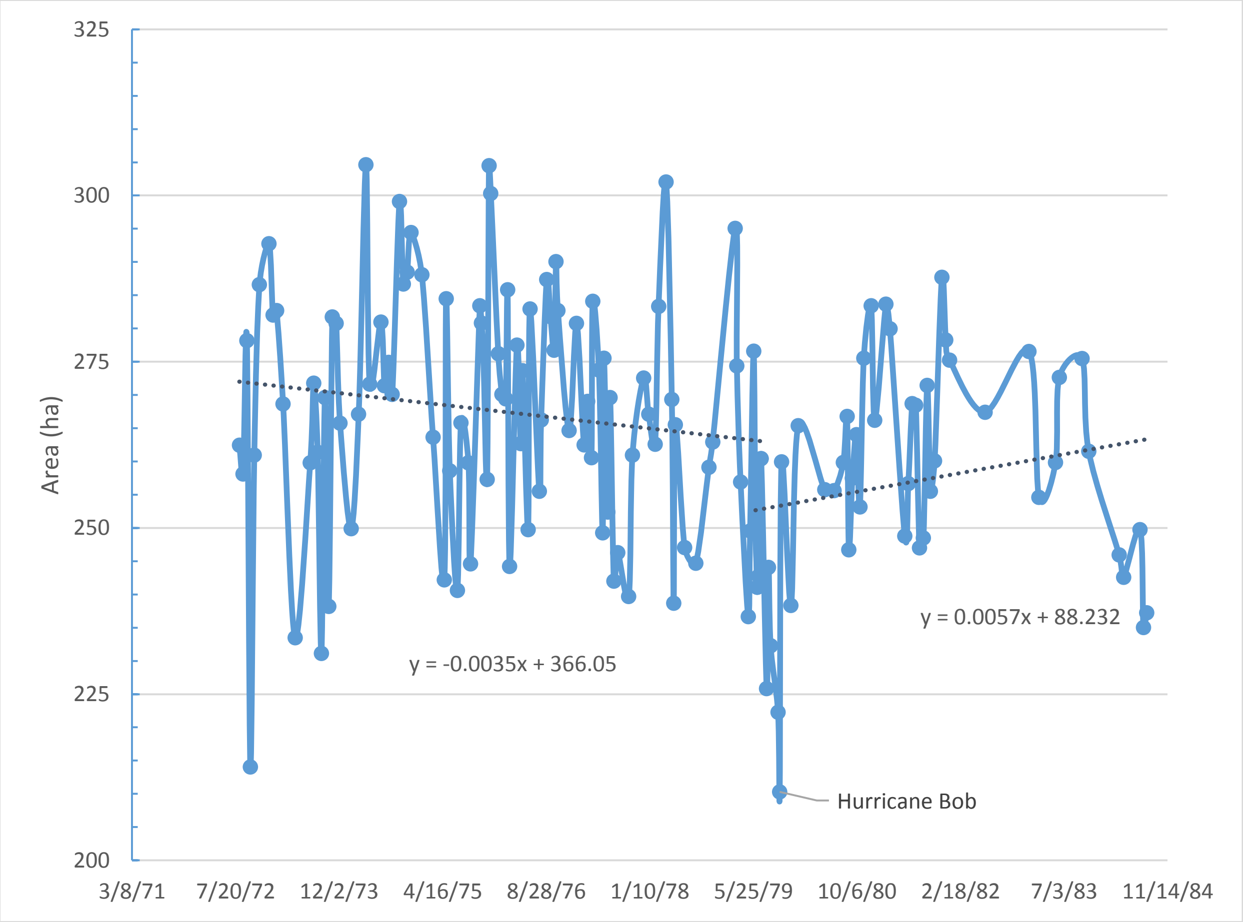

Figure 4.4 Area change on West Ship Island during Period I.

During this period, variance was 333.211. Break point analysis showed a smaller, less statistically significant break in August 1979, coinciding with the landfall of Hurricane Bob, a shift from a cool to warm PDO, and a change to a neutral ENSO period. A slight decrease in variability (322.39 to 295.32) and upward trend in area (y = 0.0057x + 88.232) magnify the changes observed during this period (Figure 4.4). However, areas become temporally more dispersed during the second sub-period, and as such reflects lower variability. The data gap during this time may be masking seasonal and storm variability, although the same pattern was also observed on ESI.

4.2.b. West Ship Island: Period II

Period II was an extremely stable period for WSI (variance = 142). Aside from a series of severe thunderstorms in the winter and spring of 1987, no major weather events occurred between the start of Period II and July 1988. For four years, WSI experienced regular seasonal fluctuations – the islands grew most in winter, shrank most in the spring, grew during the early summer, and shrank again in late summer. The pattern echoes global sea level fluctuations and showed an -0.691 R^2 between sea level and surface during that time.

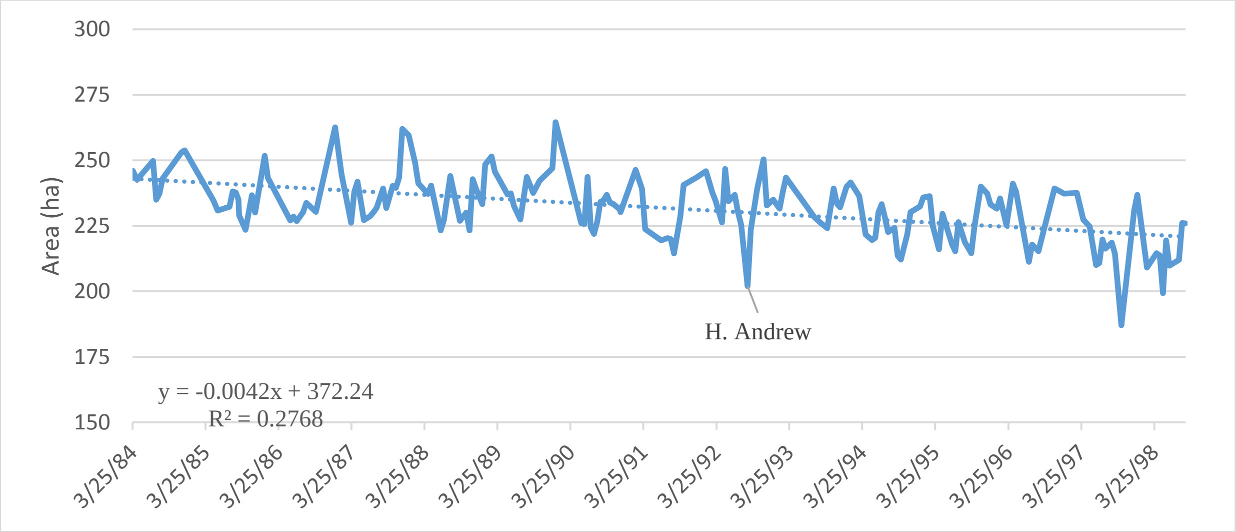

Figure 4.5 Area change on West Ship Island during Period II.

In 1988, Tropical Storm Beryl and Hurricane Florence eroded 20 ha of surface area, which was recovered by November 20, 1988. No significant events occurred between Hurricane Florence (1988) and Hurricane Andrew (1992). Hurricane Andrew eroded 25 ha of surface area from WSI – less than PBI, but more than ESI. Most hurricanes eroded more from ESI than WSI, with Andrew being one of only a handful of exceptions. The island returned to its normal seasonal fluctuations by November 1992. With relatively calm hurricane seasons up to 1995, the island experienced a slight decline in surface area during the three years between Hurricanes Andrew (1992) and Allison (June 4, 1995). Allison eroded about 12 ha of surface area, which were recovered by July 19, 1995, and then lost again after Tropical Storm Dean and Hurricane Erin made landfalls within a week of each other, eroding 12 ha more of surface area. Tropical Storm Josephine (1996) caused considerable damage on PBI, eroding 40 ha of surface area, but no data were available for evaluating Josephine's effects on WSI or ESI. WSI resumed its seasonal pattern up to September 30, 1998 when Hurricane Georges struck the island.

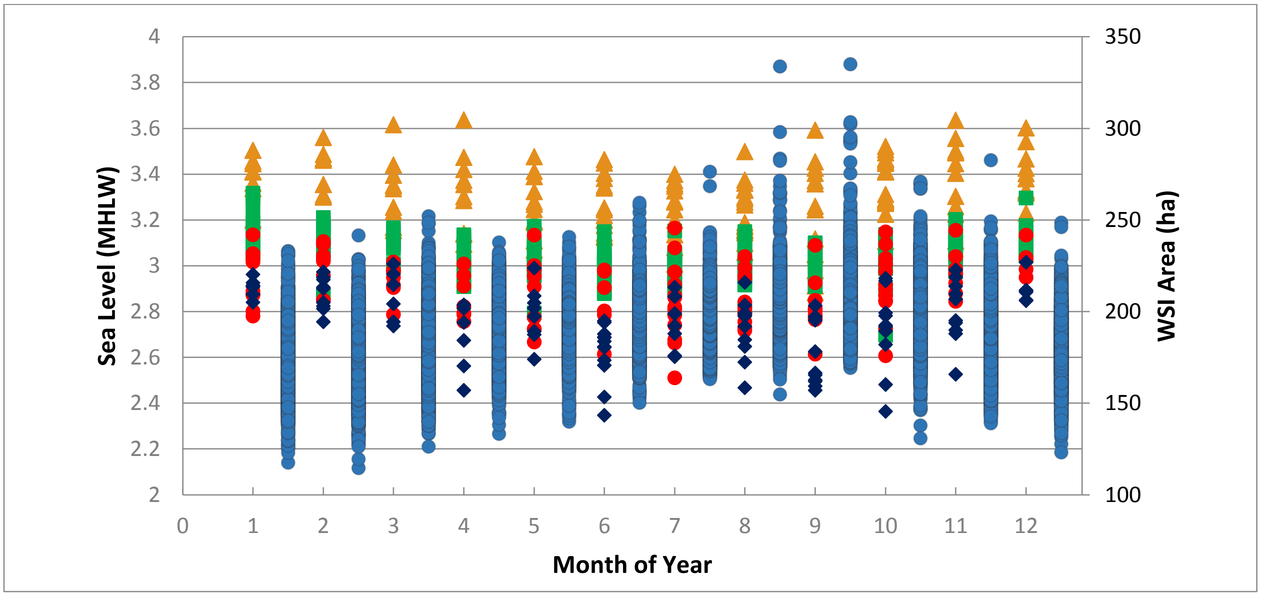

Figure 4.6 Distribution of area and sea level by month of year. Orange triangles, green squares, red circles, and blue diamonds represent WSI area for Periods I, II, III, and IV, respectively. Blue circles represent sea level gauge data from Pensacola, Florida.

Sea level and area on WSI are intertwined (Figure 4.6). A linear regression of surface area and sea level during Period II reflected a 0.56 R^2 with an F-statistic of 113. The F-statistic is a measure of the F-distribution statistic under the null hypothesis- how a proposed regression model fits the data well. When elapsed time is considered in the linear regression equation, the R^2 value increased to 0.7603 (Table 4.5). A correlation matrix using sea level and various climate factors (e.g. extreme maximum temperature and monthly total rainfall) showed similar results, with sea level showing the strongest correlation with area of all the factors (Table 4.11). The various factors grew and shrank in terms of correlation with surface area across the four time periods. For example, sea level was most strongly correlated with area during Period II (0.534 R^2) and Period IV (-0.503 R^2), correlated less strongly during Period III (-0.438 R^2), and only correlated slightly with area during Period I (-0.259 R^2). It should be noted that sea level measurements contain the maximum high-tide and highest water level measurements, which would include any storm surge measurements taken during the month, assuming the equipment survived the storm which it sometimes did not.

The most significant shift in correlation over the four time periods concerned precipitation: extreme daily precipitation and total monthly precipitation were only slightly correlated with surface area during Period I, II, and IV, but highly correlated during Period III (-0.485 and -0.595 R^2, respectively). Extreme maximum and minimum monthly temperatures also decrease in correlation during Period III. It is also worth mentioning that the correlations match the month the image was taken, even if an image was taken on January 1. An assessment considering prior month’s or prior season’s temperature, precipitation, etc. (i.e., temporally lagged correlations) may yield stronger relationships.

The seasonal and annual changes and losses during this period suggest that even under stable climate conditions with limited extreme weather events, continued sea level rise would continue to erode the islands at a rate higher than the islands are capable of compensating for with natural accretion processes. Compounded with increased sediment depletion (a problem that compounded over time), as well as dredging projects and development on neighboring islands prohibiting the natural westward translocation, the island experienced net erosion during this period driven by rising seas and extreme climate conditions.

Table 4.5 Linear regression model results for sea level and time on West Ship Island during Period II.

	Estimate	Std.Error	T-Value	Pr(>Iti)
Intercept	3.820^{02}	1.146^{+01}	33.32	2.0^{-16}
Sea Level	-4.401^{-02}	4.027^{-03}	-10.93	2.0^{-16}
Time	-4.320^{-03}	4.032^{-04}	-10.71	2.0^{-16}
R^2: 0.56444	F-Statistic: 113.1			

Table 4.6 Correlation analysis results for West Ship Island for all time periods.

Factor and R-Squared for wsi	**period I**	**Period II**	**period III**	**Period IV**	**ALL PERIODS**
Sea Level	-0.259	**-0.534**	-0.438	**-0.503**	-0.424
Time Series	-0.165	-0.526	-0.174	0.27	**-0.854**
Days Per Month Above 32°C	-0.322	-0.234	0.06	-0.279	-0.142
Days Per Month With Min Temp Below 0°C	0.268	0.331	0.17	0.391	0.157
Extreme Maximum Monthly Temperature	-0.421	-0.413	-0.037	-0.426	-0.232
Extreme Minimum Monthly Temperature	**-0.455**	-0.442	-0.196	-0.435	-0.263
Mean Monthly Temperature	-0.441	-0.477	-0.233	-0.451	-0.259
Mean Minimum Temperature	-0.448	-0.480	-0.217	-0.437	-0.270
Total Monthly Precipitation	-0.101	-0.087	**-0.595**	-0.135	-0.156
Extreme Daily Precipitation	-0.120	-0.090	-0.485	-0.193	-0.169

4.2.c West Ship Island: Period III

WSI grew steadily during the summer leading up to when Hurricane Georges made landfall on September 30, 1998 (Figure 4.7). Georges eroded 35 ha from WSI, considerably less area than was eroded on ESI (73 ha), PBI (58 ha) and, proportionally, Sand Island (6 ha). Although WSI lost 15% of its surface area, its proximity to the eye wall typically results in higher amounts of erosion. However, the eye of Georges passed directly over ESI, putting WSI on the western half of the storm where storm surge tends to be less intense. On the other hand, PBI was in the northeast quadrant of the storm, where storm surge is greatest. WSI quickly recovered from Georges, reaching 227 ha on January 19, 1999. WSI stayed above 200 ha through the start of the next hurricane season.

By July 22, 1999, WSI reached 221 ha again before Hurricane Bret washed 20 ha away on August 22, 1999. WSI stayed at 200 ha until Tropical Storm Harvey struck on September 20, 1999, temporary slowing down growth before sea level fell and the island grew to 220 ha by the end of hurricane season (-0.438 R^2). Growth from October 1999 through June 2001 was steady and relatively stable, with the island staying around 220 ha for nearly two years, with a few dates reflecting growth upwards of 20 ha, letting the island reach 245 ha before falling again, either because of a tropical storm (Beryl 2000) or thunderstorms (February 2001).

Tropical Storm Allison changed the trajectory of the island, however, causing erosion for nearly two months, before Tropical Storm Barry brought the island down to 190 ha. The island grew to 245 ha by November 16, 2001, before falling to 211 on January 3, 2002, back up to 238 on February 28, 2002, and back down to 222 on March 8, 2002, where surface area stayed until an active 2002 hurricane season started. Tropical Storms Edouard and Fay eroded 42 ha. The storms struck within five days of each other with the first image after the storms hit taken one day after

Fay made landfall. While Tropical Storm Hanna and Hurricane Isidore had considerable effects on ESI, PBI, and Sand Island, WSI lost only 1 ha between September 8, 2002 and October 2, 2002.

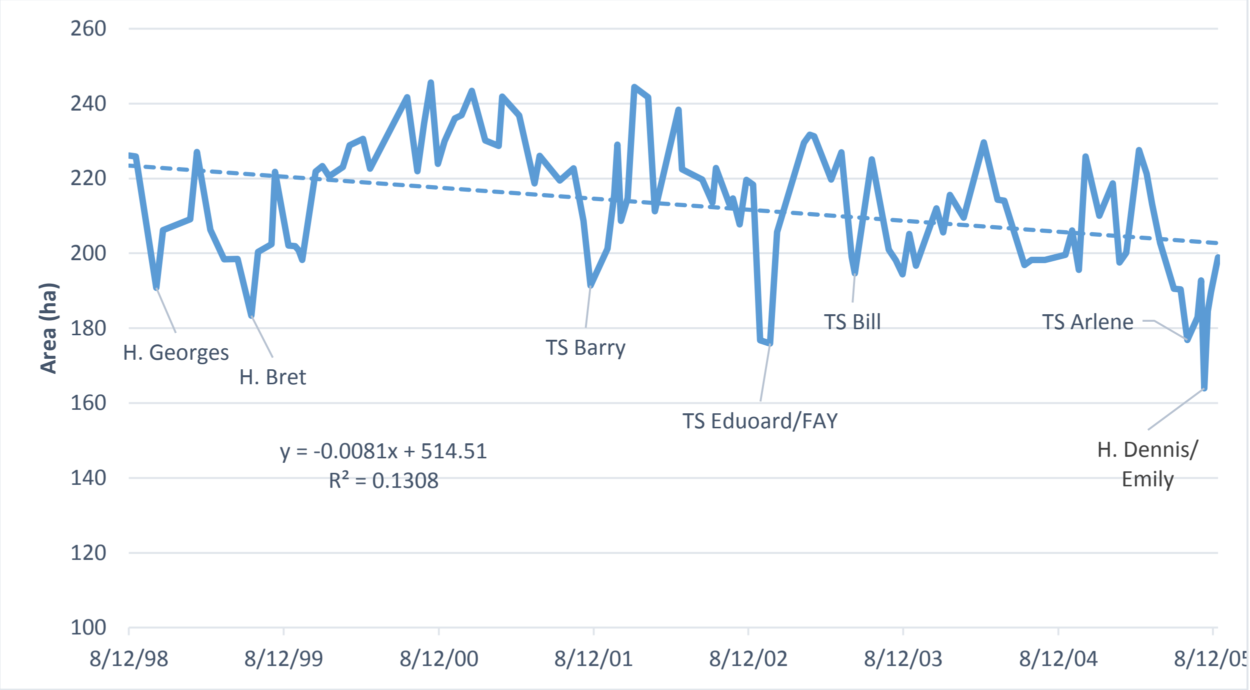

Figure 4.7 Area change on West Ship Island during Period III.

Hurricane Lili (October 3, 2002) resulted in a net gain of 30 ha before a period of rapid growth brought the island up to 227 ha on March 19, 2003. The island fluctuated little in the spring of 2003 until the start of hurricane season, when it was 225 ha on May 20, 2003. Tropical Storm Bill eroded 20 ha of area, followed two weeks later by Hurricane Claudette, which eroded 6 ha. A pause in activity between July 15 and August 31, 2003 gave the island time to rebuild slightly, growing to 205 ha on August 26, 2003, before Tropical Storms Grace and Henri struck within a week of each other, eroding 10 ha.

The winter continued as usual for WSI, growing through February, shrinking slightly through May, and growing again starting in August. Hurricane Ivan struck on September 15, 2004, and eroded 10 ha of surface area. For WSI, the first image taken after Ivan was taken two weeks later on September 29, 2004. The loss on WSI due to Ivan was again smaller compared to ESI – WSI lost 10 ha and ESI lost 40 ha. Leading into 2005, the island grew again until a strong winter storm eroded 20 ha in December 2004.

The island again recovered quickly, reaching 227 ha by February 18, 2005, but eroded at a rate of 10 ha per month between February and May 2005. At the start of the 2005 hurricane season, WSI's area was 190 ha. Tropical Storm Arlene struck on June 11, 2005, and eroded 15 ha. The island reached 192 ha again on July 14, 2005, before Hurricane Emily hit on July 20, 2005, eroding 30 ha of surface area. The island recovered yet again, reaching 198 ha six days before Hurricane Katrina made landfall on August 29, 2005.

Unlike during the other three periods on WSI, the most highly-correlated factors during Period III both involved precipitation. Extreme daily precipitation (-0.495 R^2) and total monthly precipitation (-0.602 R^2) together yielded a standard error of less than 0.0006 in a linear regression model with an intercept of 284.9527 and a coefficient of -0.0228.

4.2.d West Ship Island: Period IV

The 2005 hurricane season, while extremely destructive to WSI, left the island almost as large as it was before the season started. What happened in between, however, caused massive losses in vegetation and beachfront, accumulation of sand banks at the eastern spit, filling of inland lagoons, and collapse of the sound-side beachfront. The 2005 hurricane set the stage for continued erosion and collapse by destroying dunes and delicate beachfront. Katrina eroded 40 ha of surface area – only 10 ha more than Hurricane Emily, which struck a month before Katrina. Rita, which hit less than a month after Katrina, eroded 20 ha. The 2005 hurricane season eroded 105 ha of surface area in all – about half of the island’s total area and three-times as much area as was normally exchanged during a typically hurricane season on WSI.

The island recovered slightly, reaching 217 ha by February 7, 2006. Tropical Storms Alberto and Chris each eroded 20 ha of surface area from WSI, though by the end of the season the island had grown to 226 ha. By the start of what would become a very active 2007 hurricane season, the island shrank back down to 201 ha. Tropical Storm Barry hit on the first day of hurricane season (June 1, 2007) and eroded 67 ha of surface area from WSI. Across all islands, Tropical Storm Barry was one of the most erosive weather events in the 40-year study period. Barry was not particularly strong – its highest 1-minute sustained winds were 95 km/hr – but brought intense low pressure (997 mb), 200 mm of rain and a considerable storm surge (2 m). No other events occurred between May 25 and June 2, which could explain the losses observed across the entire island chain.

An unnamed tropical depression passed over the study area on September 21, 2007 eroding, another 33 ha of surface area, though the island reached 210 ha on November 1 before Tropical Storm Olga made landfall and eroded another 10 ha. Barry and the unnamed tropical depression both occurred one day before the images were taken, which could make the initial overwash appear greater than other storms. Nine days after Barry struck, the island’s area increased 50 ha to 194 ha – less than 10 ha smaller than its May 1, 2007 area. Likewise, the day after the unnamed tropical depression struck, WSI appeared to lose 33 ha of area, but eight days later the island had actually gained 10 ha from its size less than a week before the storm struck.

The same cannot be said about the 2008 hurricane season – WSI started the hurricane season at 208 ha and finished at 160 ha. Most of the damage occurred between August 7, and

September 8, when both Tropical Storm Fay and Hurricane Gustav made landfall. Together, the two storms eroded 55 ha of surface area. Cloud cover on the August 15 and 31, Landsat 7 images and the August 23, 3008 Landsat 5 image make attribution to the two storms individually impossible. Hurricane Ike (September 13, 2008) did more damage on PBI and Sand Island than WSI or ESI, but still made an impact, nonetheless.

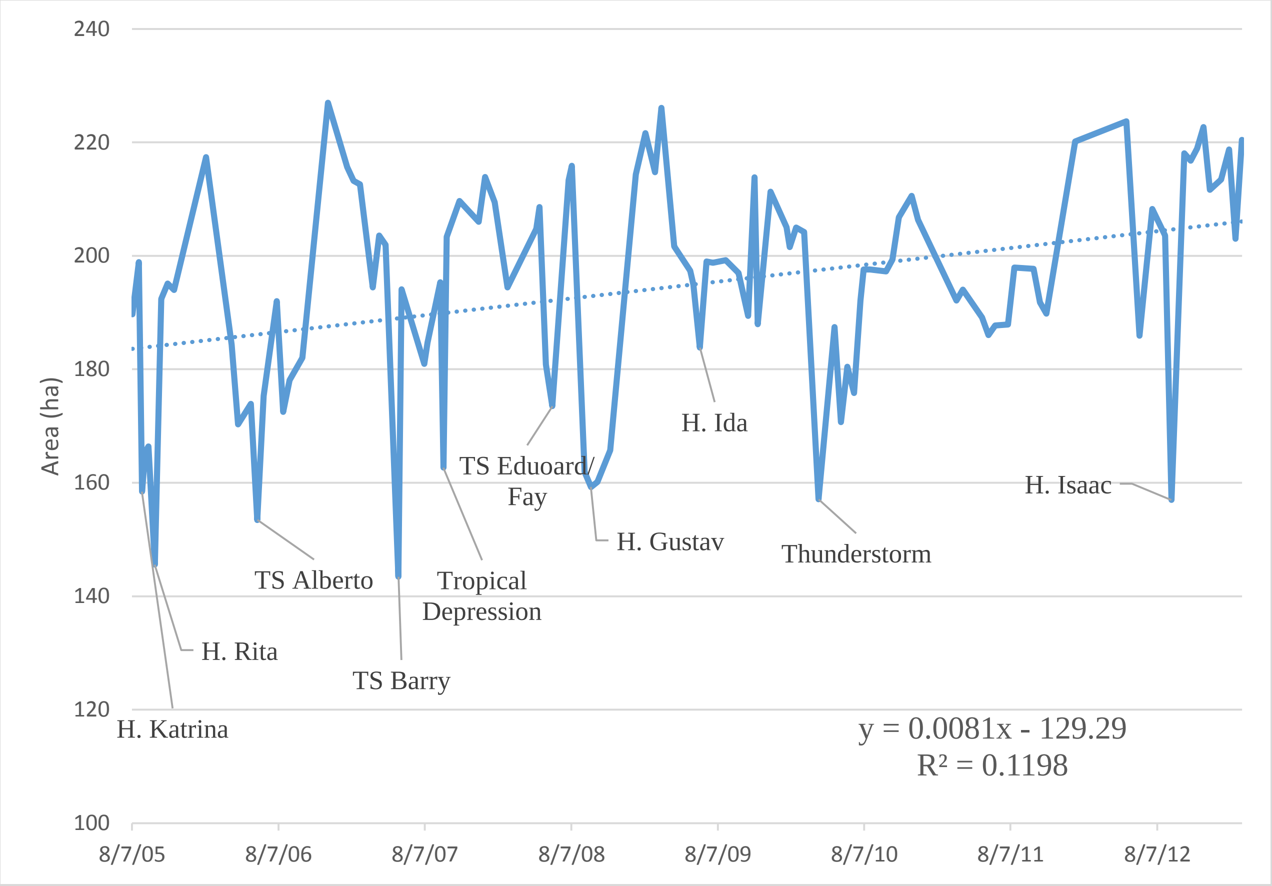

Figure 4.8 Area change on West Ship Island during Period IV.

By February 7, 2009, WSI was 221 ha, though it gradually shrank to 194 ha by the start of the 2009 hurricane season. With no hurricanes making landfall until after the end of hurricane season, the island never dipped below 185 ha during the summer, growing back to 213 ha by November 6, 2009. Hurricane Ida (November 9, 2009) eroded 25 ha of surface area that was recovered by December 16, 2009. WSI stayed around 200 ha until a strong thunderstorm in late February 2010 eroded 50 ha of surface area – 10 ha more than the erosion caused by Hurricane Katrina.

At the start of the 2010 hurricane season the area of WSI was 170 ha. WSI grew to 180 ha by June 26, 2010. An unnamed tropical depression struck on July 9 and eroded 6 ha, but resulted in a net growth of 12 ha less than two weeks later. The island remained at 197 ha from the end of July through November 1, the end of hurricane season. The island grew slightly in the winter, to 210 ha on December 3, 2010, then shrank again to 187 and stayed there until July 31, 2011, when it started growing again to 197 ha on October 3, 2011 and to 220 ha on January 15, 2012. The island's area stayed at 223 ha until the start of hurricane season. A severe thunderstorm on June 11, 2012, eroded 38 ha, which was mostly recovered, with the island reaching 208 ha by July 25, 2012. Three days before Hurricane Isaac made landfall, WSI was 203 ha. Thirteen days after Isaac, the island's area was 156 ha – 47 ha smaller. But the island rebounded quickly, reaching 218 ha by October 13, 2012, where the surface area remained through April 2013

4.3 East Ship Island: Summary

ESI experienced the greatest amount of loss of all four islands. Even though ESI was 40% smaller than WSI at the start of the study period, it experienced more total change. The data show ESI experienced 6680 ha of change - 3373 ha loss and 3307 ha gain. Of the 3373 ha of loss, 2706 ha (80%) resulted from catastrophic events. Hurricanes account for at least 1270 ha of that loss. Winter storms and thunderstorms account for 732 ha and 704 ha each, respectively. In all, 59% of all observed change on ESI resulted from catastrophic events (Figure 4.15).

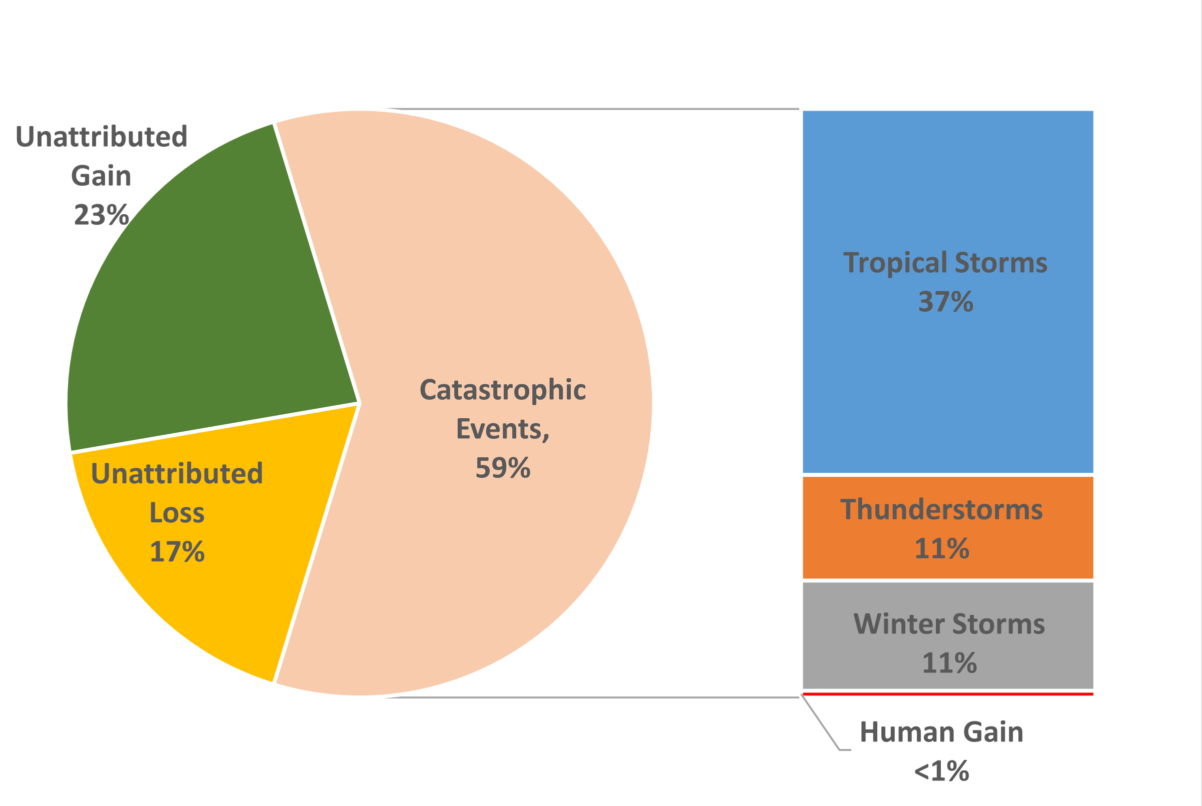

Figure 4.9 Area change on East Ship Island by cause.

The western spit of ESI grew and receded through the years. Hurricane Georges (1998) split ESI into two islands. On November 29, 2000, the third island was less than 150 m away from ESI. By March 25, 2001, the two eastern islands were temporarily joined by an extending hook from the larger part of ESI. But by April 06, 2001, the islands were detached again. Imagery from 2003 show three distinct channels dug completely across the islands from north to south. From January through April 2004, ESI nearly collapsed, splitting into four smaller islands, three of which with areas less than 10 ha.

Tropical cyclones cause more damage more frequently and more intensely on ESI than any other island in the study area (Figure 4.15). In fact, hurricanes that barely register on the other islands have considerably large impacts on ESI. Hurricanes Eloise, Florence, and Isidore caused little to no discernable damage on WSI, but have similar impacts on ESI to Andrew on WSI. In many ways, ESI shelters WSI by absorbing wave damage from storms approaching from the southeast, and the catchment basin between the two islands serves as a depository for sediment migrating westward toward WSI. Thunderstorms and winter storms caused about the same percentage of overall change (about 11% each), but because the impact of tropical cyclones was so much greater, none caused comparatively significant damage. Of the 25 most erosive events for ESI during the study period, there were 13 tropical cyclones, 6 thunderstorms, and 6 mid-latitude cyclones or winter storms (Figure 4.10). Nine of those 25 events occurred within the last eight years of the study period (Period IV), 11 during Period III, and four during Period II.

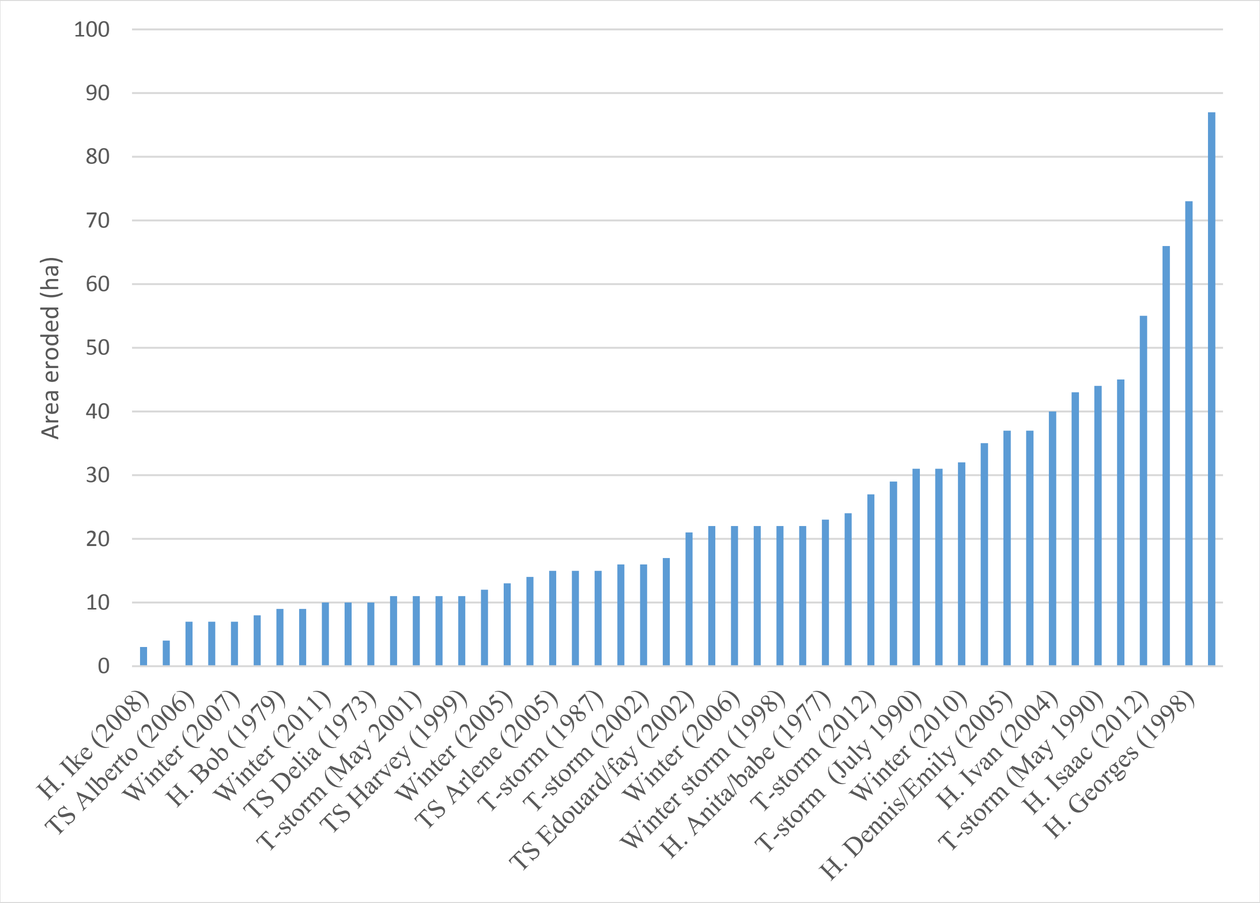

Figure 4.10 Most impactful events on East Ship Island by hectares (ha) eroded.

4.3.a East Ship Island: Period I

Hurricane Dawn caused significant erosion at the start of the study period for ESI, washing away 35 ha of surface area, and the island yo-yoed during the rest of 1972, from 136 ha after Dawn to 178 on October 18, to 150 ha on November 12, and 186 ha on December 28, 1972. The island reached 194 ha on January 16, 1973. Like with WSI, some of variance could be attributed to changes in sensors before the launch of Landsat 5. Figure 4.16 shows the two patterns of erosion and growth during this time period. The first series shows overall surface area loss with higher variability, and the second series shows overall growth and less variability. Overall, however, the trends observed in Period I of ESI match closely to those observed on WSI.

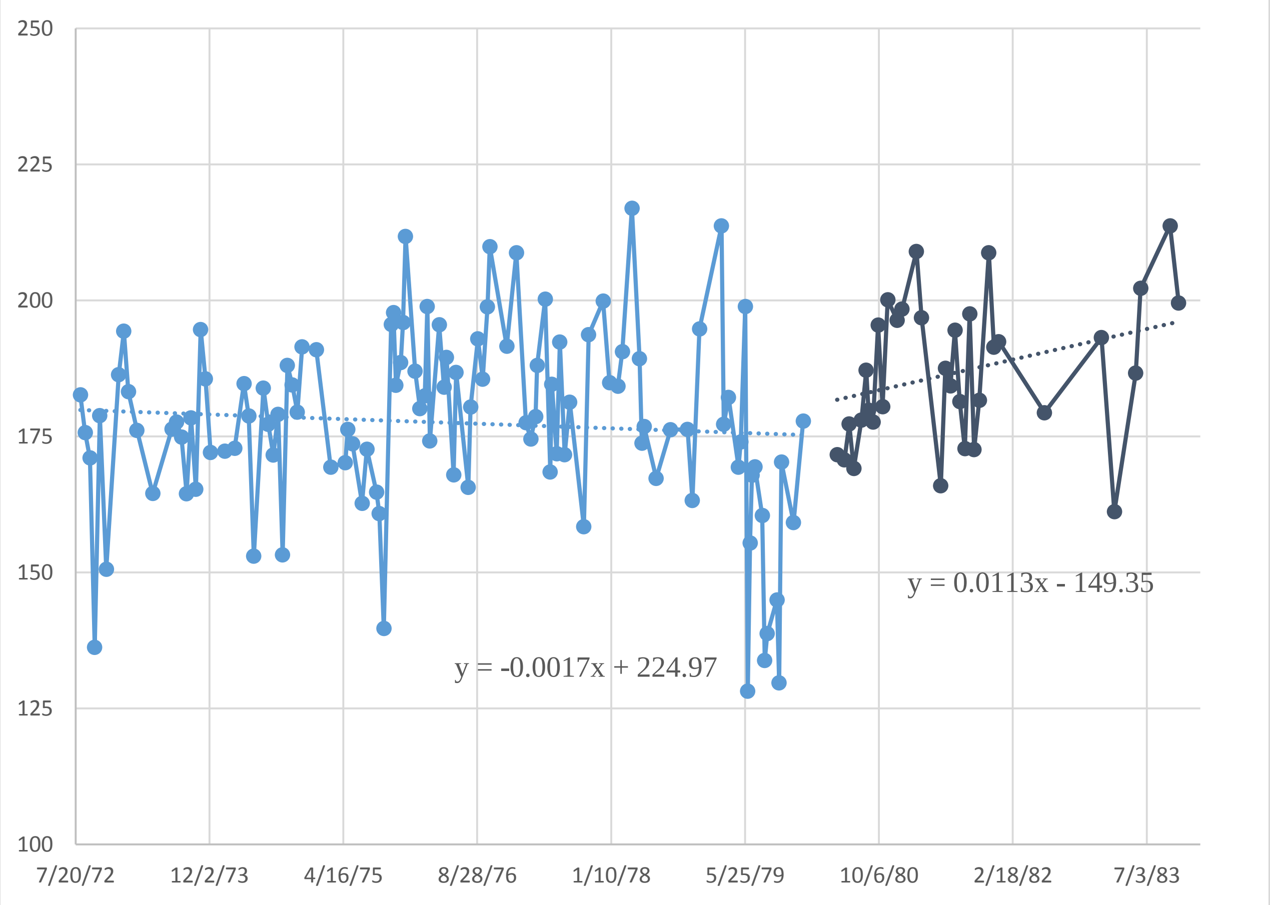

Figure 4.11 Area change on East Ship Island during Period I. A break-point analysis showed two linear trends dissected in 1979.

4.3.b. East Ship Island: Period II

Hurricane Elena eroded 19 ha from ESI on September 2, 1985 – a loss that was recovered by January 15, 1986, when the island reached its seasonal maximum at 168 ha. The island shrank slightly in the spring – about 10 ha, before growing again the next winter. On January 2, 1987, ESI reached its seasonal maximum at 176 ha, though a series of severe storms in February and March eroded 30 ha, reducing the surface area to 148 ha. At the start of the 1987 hurricane season, ESI was 145 ha and grew to 161 ha by the end of the hurricane season on November 1, 1987.

The island grew back to 174 ha by December 4, 1987, and remained near that size until February 6, 1988. Again the island shrank during spring as sea level rose and thunderstorms moved through, leaving the island at 146 ha at the start of hurricane season. Imagery for ESI during the 1988 hurricane season was spotty – there was a six-week gap between July 31 and September 17, 1988, during which time both Tropical Storm Beryl and Hurricane Florence made landfall. The island lost 22 ha of surface area between the two images, though the loss was more likely due to Hurricane Florence given the time between the landfall of Tropical Storm Beryl and the next image date (27 days). ESI did not recover until past the end of Hurricane season and reached 172 ha by February 1989.

The 1989 hurricane season was a quiet one with no tropical cyclones making landfall within 100 km of the study area and no major losses or gains observed during the entire season. The island reached maximum size on February 14, 1991, at 165 ha, slightly smaller than the previous years' maxima - 1992 mirrored the previous three years exactly: the year started with a higher area, then changed little during the spring, decreasing slightly up to the start of hurricane season when it grew slightly again. A tropical depression eroded 12 ha in late June 1992 and Hurricane Andrew eroded an unknown amount of area in August 1992. ESI was covered by clouds on images taken on August 27, 1992 – just one day after Hurricane Andrew made landfall, and again on September 4, 1992. Virtually no change in area occured between July 26, 1992, and September 12, 1992, on ESI – a signal that significant erosion must have taken place as the island typically grows in the absence of severe hurricanes. On WSI, PBI, and Sand Island, erosion from Hurricane Andrew was considerable: 25 ha on WSI, 40 ha on PBI, and 3 ha on Sand Island. While the impact of Hurricane Andrew on ESI cannot be measured using the methods in this study, it is reasonable to assume the hurricane had a considerable impact on the islands given the damage to the surrounding area and the lag rate of recovery following landfall. ESI has been more vulnerable to erosion than the other islands, and given the island's history with intense tropical cyclones, Andrew could have eroded anywhere between 20 and 50 ha of area, which is not calculated in the totals of catastrophic damage.

Table 4.7 Sea level correlation with change in surface area on East Ship Island.

ESI Sea Level	**Period I**	**Period II**	**Period III**	**Period IV**	**ALL PERIODS**
Sea Level (Pensacola, Fla.)	**-0.461**	**-0.612**	-0.646	-0.473	-0.419
Highest (Dauphin Island)	-0.143	-0.166	-0.468	-0.322	-0.349
MHHW	-0.380	-0.482	**-0.726**	-0.456	-0.535
MHW	-0.353	-0.486	-0.716	-0.418	**-0.550**
MSL	-0.392	-0.523	-0.719	-0.434	-0.486
MTL	-0.382	-0.521	-0.712	-0.410	-0.490
MLW	-0.385	-0.521	-0.678	-0.395	-0.399
MLLW	-0.378	-0.520	-0.669	-0.415	-0.420
Lowest	-0.384	-0.528	-0.649	**-0.475**	-0.309

The island grew slightly to 168 ha by November 15, 1992 and shrank again during the spring of 1993. With no major weather events occurring in 1993, the island experienced very little change, experiencing 50 ha of change and a net gain of 9 ha of area during the year. Although it resulted in a net loss of 9 ha, 1994 mirrored 1993 almost exactly – small losses in spring, small gains in summer, a slight loss in fall, and moderate gains in winter. Tropical Storm Debby eroded 10 ha of area in September, but no other weather events were signaled in the data.

Unlike 1993 and 1994, 1995 was an extremely active year for severe weather events with five events affecting the study area. A flooding event in May 1995 eroded 7 ha and Hurricane Allison, striking a month later, eroded another 8 ha. The island recovered slightly then stabilized at about 150 ha between Hurricane Allison and Tropical Storm Dean, which struck on July 29, 1995. Tropical Storm Dean and Hurricane Erin both made landfall within a week of each other, making it difficult to attribute the erosion afterward to one or the other. The two storms eroded about 20 ha of surface area. ESI recovered by December 10, 1995, reaching 172 ha and remaining there until a low pressure system in late March eroded 20 ha.

The island bounced back to 174 ha by mid-April 1996 and fell back to 160 by the start of the 1996 hurricane season. No tropical cyclones affected WSI or ESI during the 1996 hurricane season, but the island eroded between each image anyway – ending the season at 158 ha after dipping down to 137 ha in August and climbing back up to 151 by September. The island reached 163 ha, its seasonal maximum, on April 3, 1997 – the latest maximum observed of any season during the study period. This late-season maximum was partly the results of low growth in the 1996-1997 winter season and early spring erosion in February and March.

At the start of the 1997 hurricane season, the island fell to 136 ha. The island then grew slowly to 141 ha and stayed around 140 ha through the end of hurricane season. The winter maximum reached 175 ha on December 31, 1997, though a low pressure system moving through the area on February 15, 1998 eroded 25 ha, reducing the island to 148 ha at the start of the 1998 hurricane season. During the early summer months of the 1998 hurricane season, the island shrunk and grew – from 142 ha in June to 135 ha in July, 152 ha in early August, 160 ha in late August, and down to 87 ha following the landfall of Hurricane Georges.

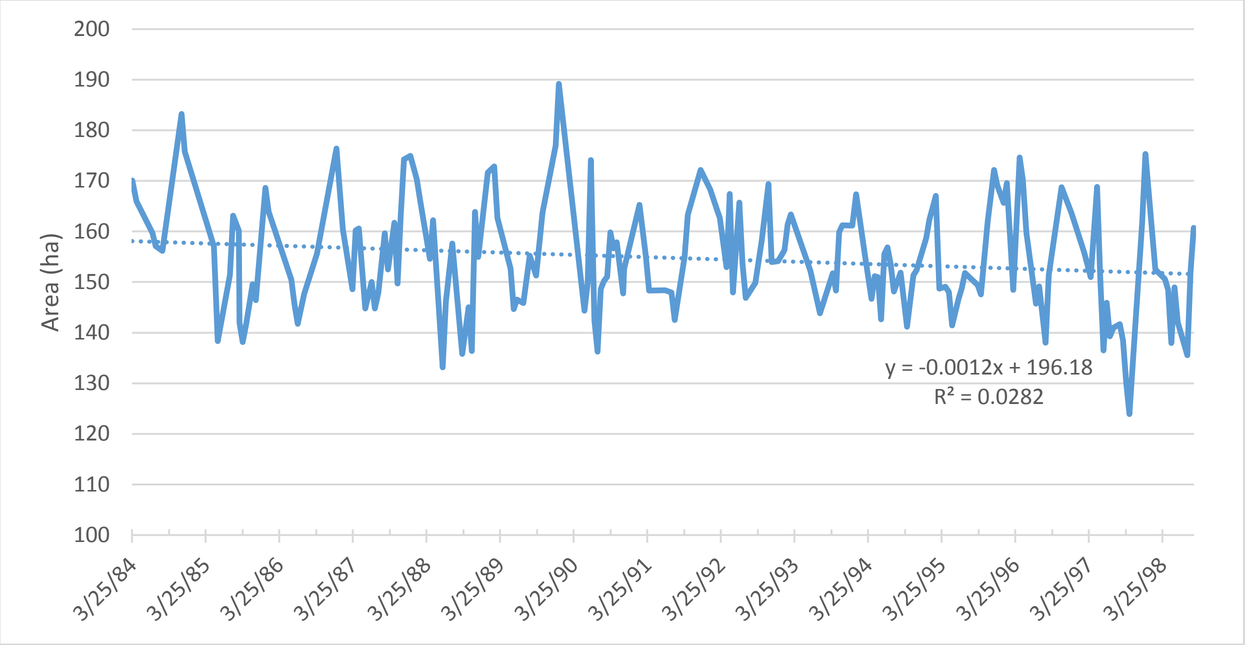

Figure 4.12 Area change on East Ship Island during Period II. The linear trend during this period is y = -0.0012x + 196.18 with an R^2 value of 0.0282.

4.3.c. East Ship Island: Period III

Georges created what was known for three years as the "Georges cut," a third intermittently-submerged island located between WSI and ESI. From this point forward the third island's area was calculated as part of ESI's area. The island never exceeded 40 ha and grew eastward toward ESI, not westward as was expected with littoral drift pushing sediment from ESI to WSI. The third island began to develop vegetation in the summer of 2000 and temporarily rejoined ESI by March 25, 2001. Hurricane Georges eroded more than half of ESI, about 80 ha of surface area. The island staggered back to its pre-Georges area, jumping from 87 ha on October 15, 1998, to 120 ha on October 31, 1998, to 160 ha by January 3, 1999.

By January 19, 1999, the island had nearly reached its 1998 maximum at 171 ha, though a late January thunderstorm eroded more than 45 ha of area, bringing it back down to 127 ha.

Although the storm occurred in the winter, it had the characteristics of a simple thunderstorm and was calculated as such. The 1999 hurricane season was relatively quiet – Hurricanes Bret and Harvey eroded a combined 20 ha, which was quickly recovered by October 26, 1999. The island reached its next maximum on May 29, 2000, at 180 ha, though a June thunderstorm eroded about 30 ha of area, leaving the island at 157 ha at the start of the 2000 hurricane season. The summer growth brought to island back up to 187 ha by July 24, 2000, but Tropical Storm Beryl (August 6, 2000) erodes 45 ha of area that was nearly fully recovered during the following winter – the island reached its maximum area on January 8, 2001, at 179 ha. The island shrank as sea level rose in the spring, down to 164 ha near the start of hurricane season on May 24, 2001.

Table 4.8 Linear regression model results for sea level and time on East Ship Island during Period III.

	Estimate	**Std.Error**	**T-Value**	**Pr(>Iti)**
Intercept	-1.145^{+02}	2.187^{01}	-5.235	2.4^{-07}
Sea Level	-4.798^{-03}	6.401^{-03}	-0.750	2.5^{-7}
Wsiarea	1.179e+	3.475^{-02}	33.924	2.0^{-16}
R^2: 0.7207	F-Statistic: 671.8			

Tropical Storm Allison (June 11, 2001) initially eroded 12 ha of surface area, but its effects lingered throughout the summer as the island continued to erode down to 128 ha by July 19, 2001, departing from the normal pattern of landfall-recovery observed in most other years. Tropical Storm Barry struck the coast on August 3, 2001, eroding another 15 ha on ESI. Barry's effects were more temporary, with the island reaching 201 ha by February 28, 2002 – the first time ESI grew above 200 ha since September 28, 1983. A severe winter storm in early March 2002, however, eroded 40 ha, bringing the area down to 160 ha. ESI continued to erode steadily until October 18, 2002. The 2002 hurricane season was unusually active with six storms impacting ESI: Tropical Storm Bertha, Tropical Storm Edouard, Tropical Storm Fay, Tropical Storm Hanna, Hurricane Isidore, and Hurricane Lilli eroded a combined 56 ha of area – more than one-third of the island’s total area before hurricane season started that year. But the island quickly recovered, reaching 203 ha by January 14, 2003. Like the winter of 2002, the rapid growth was short-lived: a severe thunderstorm in February 2002 eroded about 70 ha of area and temporarily destabilized the island as it eroded to 89 ha by April 20, 2003 – more than half of its January size.

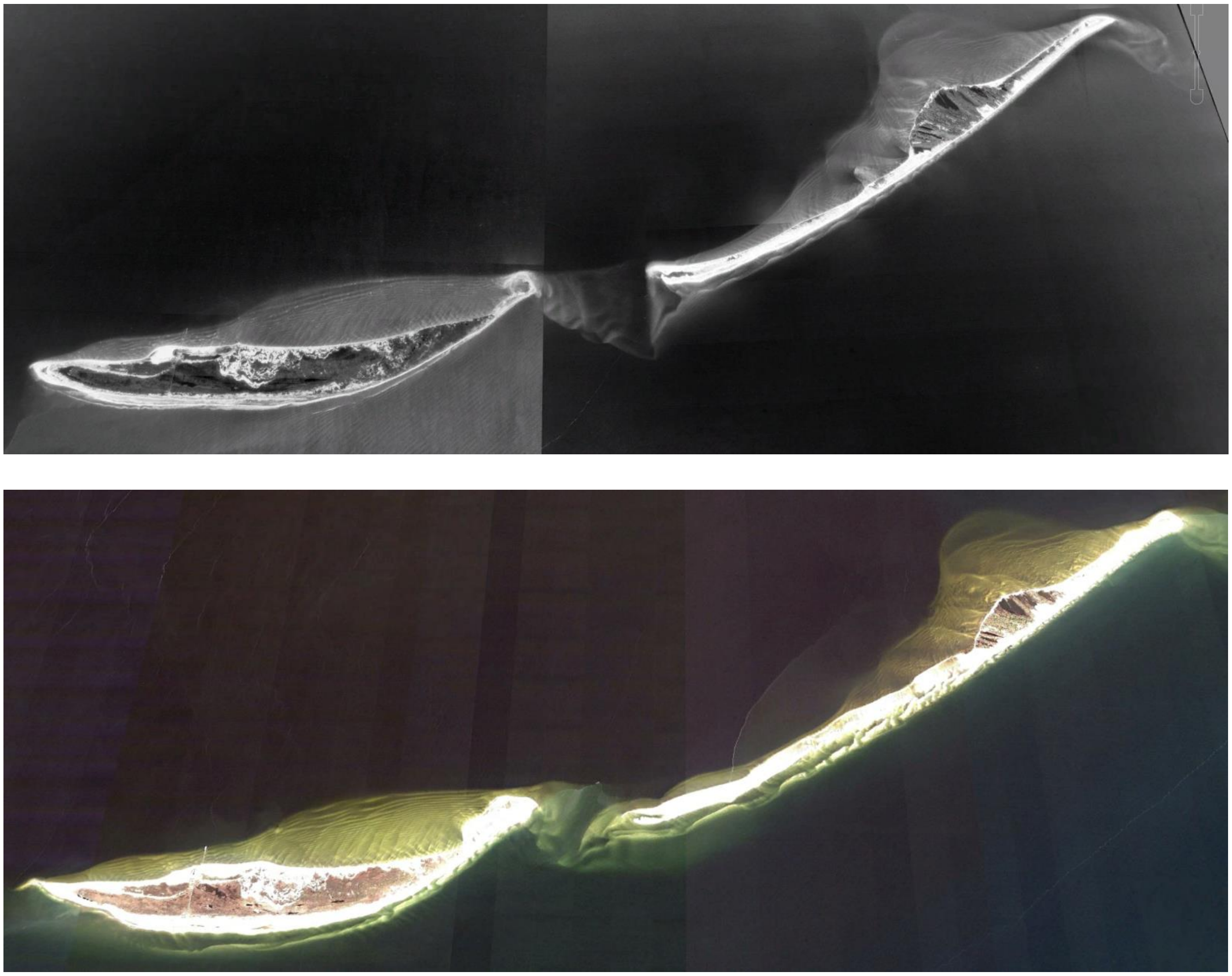

Figure 4.13 Change in distance between West Ship Island and East Ship Island. Top: An aerial image taken in February 1992. Bottom: An image taken of the islands in 2003, showing a decrease in the amount of space between WSI and ESI from 290 m in 1992 to 185 m in 2003.

By the start of hurricane season, the island reached 130 ha. Another active hurricane season, the 2003 storms (Tropical Storm Bill, Hurricane Claudette, Tropical Storm Grace, and

Tropical Storm Henri) eroded a combined 30 ha of surface area on ESI. By the time the 2003 hurricane season ended, however, the island was 10 ha bigger than when it started – about 140 ha – and continued to grow into the winter in stair-step fashion: 148 ha by November 14, 2003, 173 ha by November 30, 2003, and 195 ha by January 1, 2004. Another winter storm eroded 20 ha of area between February 18 and March 21, 2004, and for the third consecutive year the island experienced continued spring and summer gradual erosion, leaving the island at 132 ha two days before Hurricane Ivan made landfall on September 15, 2004. Ivan eroded 40 ha of area, but ESI recovered by October 15, 2004.

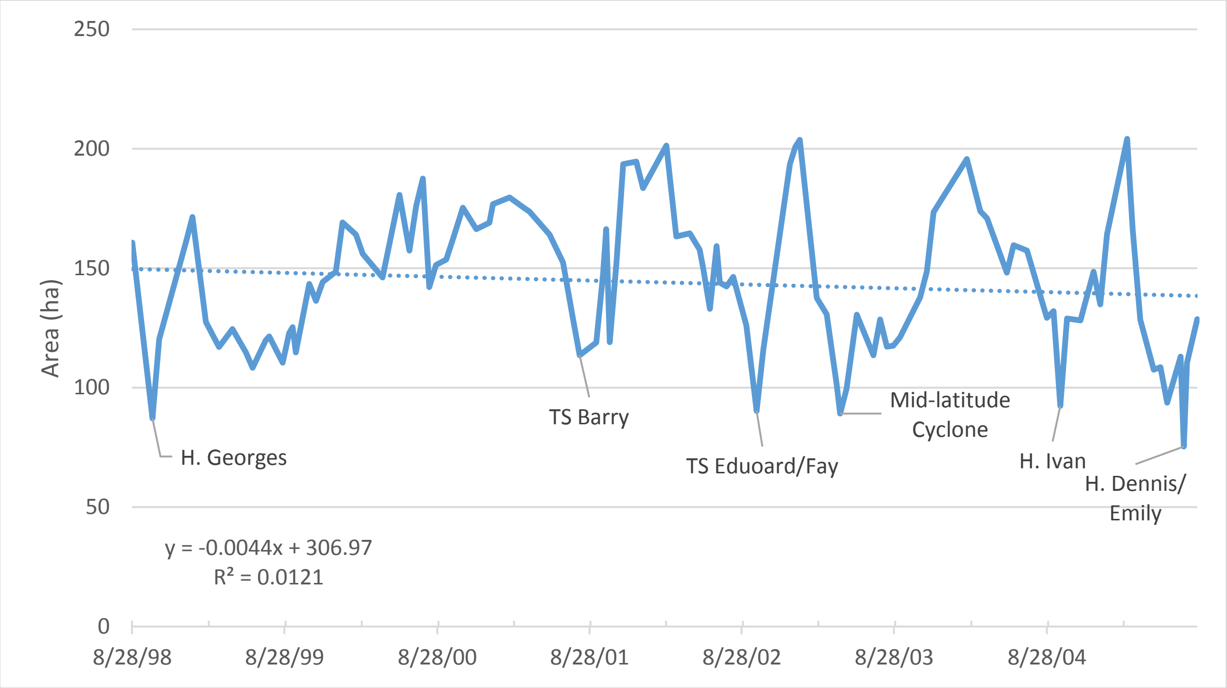

Figure 4.14 Area change on East Ship Island during Period III.

ESI reached 204 ha by February 18, 2005 – three years in a row the island climbed to its highest total surface area in more than 20 years. A severe low-pressure system in mid-March 2005 repeated the 2002, 2003, and 2004 pattern, eroding 40 ha immediately and causing a trickle-down effect that left the island at 108 ha by the start of the 2005 hurricane season. The 2005 season started with Tropical Storm Arlene, which eroded 15 ha, which was recovered by July 14, 2005. Hurricane Emily struck next on July 20, 2005, eroding 30 ha of area, which was recovered by July 30, 2005. Leading up to Katrina, the island experienced high variability, starting the year at 164 ha, then climbing to 204 ha by March, then falling back to 164 ha by the end of March, falling again to 128 ha by April, 107 ha by May, and growing and receding during multiple hurricane events.

4.3.d. East Ship Island: Period IV

The transition from a slowly shrinking transgressive barrier island to a near-relic island occurred literally overnight. Hurricane Katrina struck the area on August 29, 2005, and eroded 72 percent of the island away (see 5.16 Hurricane Katrina). The rebound from the 2005 hurricane season initiates the islands most recent phase, defined primarily by rapid recovery but also several near-complete overwash events. During the 2005 hurricane season, four cyclones eroded a combined 146 ha of surface area between June and October, more than the entire surface area of the island in May. The island's maximum winter area that year was 77 ha (January 2005), less than half its previous year's maximum of 204 ha (March 2005). While 2006 was a quiet year, two tropical storms made landfall near the study area in 2007. Tropical Storm Barry, which struck Florida on June 1-2, 2007, eroded 6 ha of surface area. Hurricane Humberto also had a noticeable impact on ESI on September 13, 2007, eroding 10 ha of surface area. The next major storm for ESI was Hurricane Gustav (2008), which eroded about 30 ha of area – 40% of its area before the storm hit. The island was hit again less than two weeks later by Hurricane Ike, which eroded another 3 ha.

The island reached 100 ha by February 23, 2009, but lost another 15 ha by April 20, 2009, as sea level began to rise again. By the time the 2009 hurricane season began, sea level rise and a handful of thunderstorms reduced the island to about 60 ha. A quiet hurricane season allowed the island to grow during the 2009 summer, reaching 88 ha by November 6, 2009. A late hurricane, Ida, eroded about 16 ha from the island on November 9, 2009, but ESI fully recovered by December 16, 2009. The island remained stable during the winter until an early spring storm eroded 32 ha between March 10, 2010, and April 15, 2010.

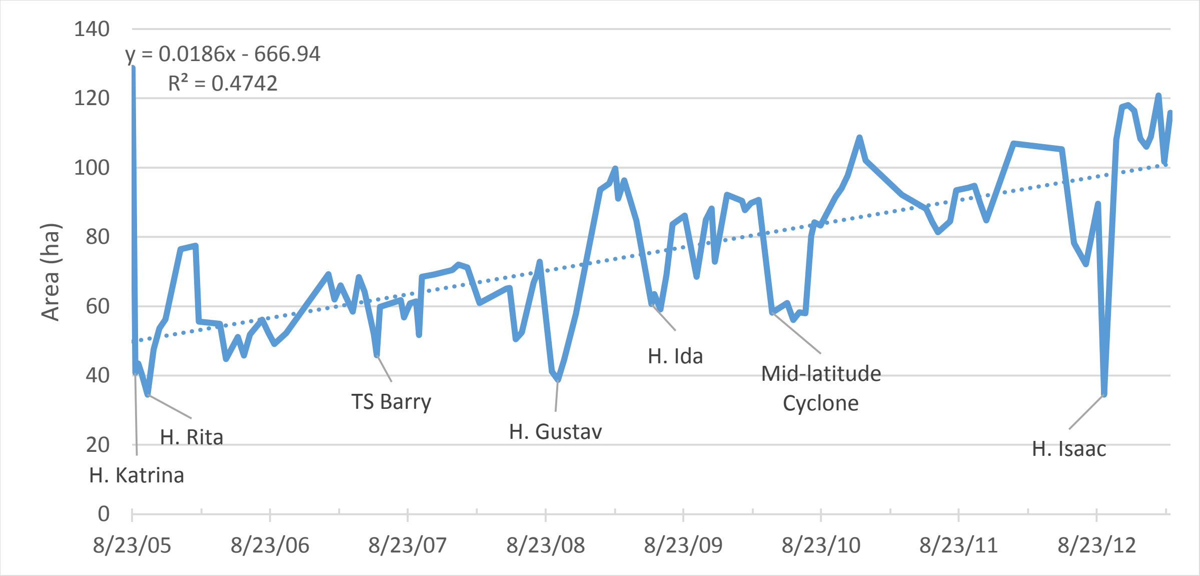

Figure 4.15 Area change on East Ship Island during Period IV.

ESI stayed around 60 ha until a tropical depression on July 9, 2010, pushed an offshore sandbar toward the island and the total surface area jumped from 58 ha to 80 ha. With no more hurricanes in the 2010 season, ESI surface area increased to 108 ha by December 3, 2010. The island grew and shrank little (less than 10 ha) between December 2010 and November 2011. By May 22, 2012, the island stabilized at around 105 ha until a severe thunderstorm on June 12, 2012, eroded about 30 ha of surface area. ESI partially recovered by August 26, 2012, reaching 90 ha, but Hurricane Isaac (August 29, 2012) washed away another 55 ha of surface area. The island recovered quickly, however, reappearing in October at 108 ha, as a result of several sandbars washing toward the island and rapid growth of the island’s eastern spit.

4.4. Petit Bois Island: Summary

Hurricanes caused 27% of all change on PBI from 1984-1998. Thunderstorms and mid-latitude cyclones caused 13% and 14% of change, respectively – equal to the amount of change caused by hurricanes. However, when only considering event damage and not accretion, winter storms and thunderstorms eroded 800 ha more than all hurricanes combined. More than 2100 thunderstorm events and 150 mid-latitude cyclone events occurred over the study area during periods II-IV on PBI, whereas only 43 tropical cyclones came within 200 nautical miles of the study area during the study period (NOAA 2013). About 2% of all thunderstorm events were observed in the data, whereas one-third of mid-latitude cyclones caused noticeable damage, and 43 of 43 tropical cyclones showed up in the data record as major events. The distribution of events eroding 20, 30, and 40 ha of area or more increased over time.

PBI experienced higher rates of variability and sensitivity to changes in sea level than the other islands in the study area. Together sea level and time yielded an R^2 value of 0.771 in a linear regression model, with an F-statistics of 598.7 (Table 4.9). Possibly due to its distance from WSI and ESI, the storms which caused the most amount of damage on PBI were relatively minor events on the other islands. Unlike on ESI where the majority of major events were tropical cyclones, 13 of the 25 most erosive events on PBI were not hurricanes or tropical cyclones, but rather thunderstorms and mid-latitude cyclones, and each system eroded more surface area than loss experienced on other islands. The increase in average loss per major event (20 ha for WSI and 40 ha for PBI) could be due to the larger size of the island (simply that it has more to lose), because its position in the island chain or proximity to extreme events made it more susceptible to erosion, because vegetation on the island varies and is more easily destroyed or removed, or because the beach front is in a different phase (transgressive versus regressive or dissipative). There is also a disproportionate distribution of erosion per event toward periods III and IV (Figure 4.16).

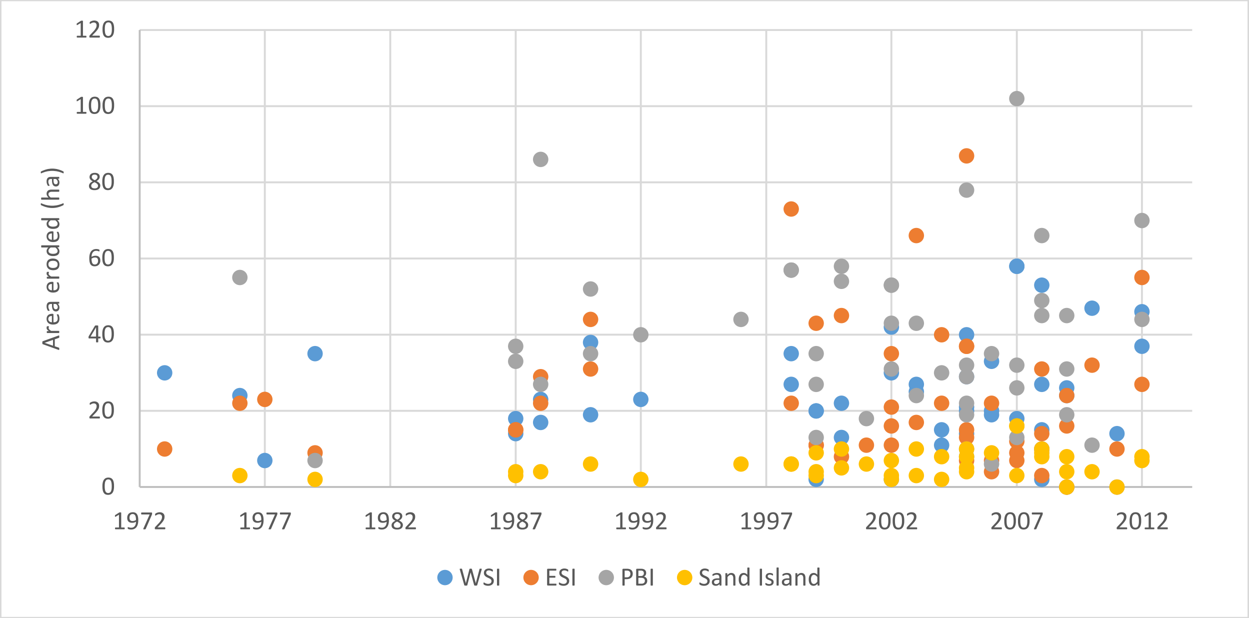

Figure 4.16: Distribution of events over time.

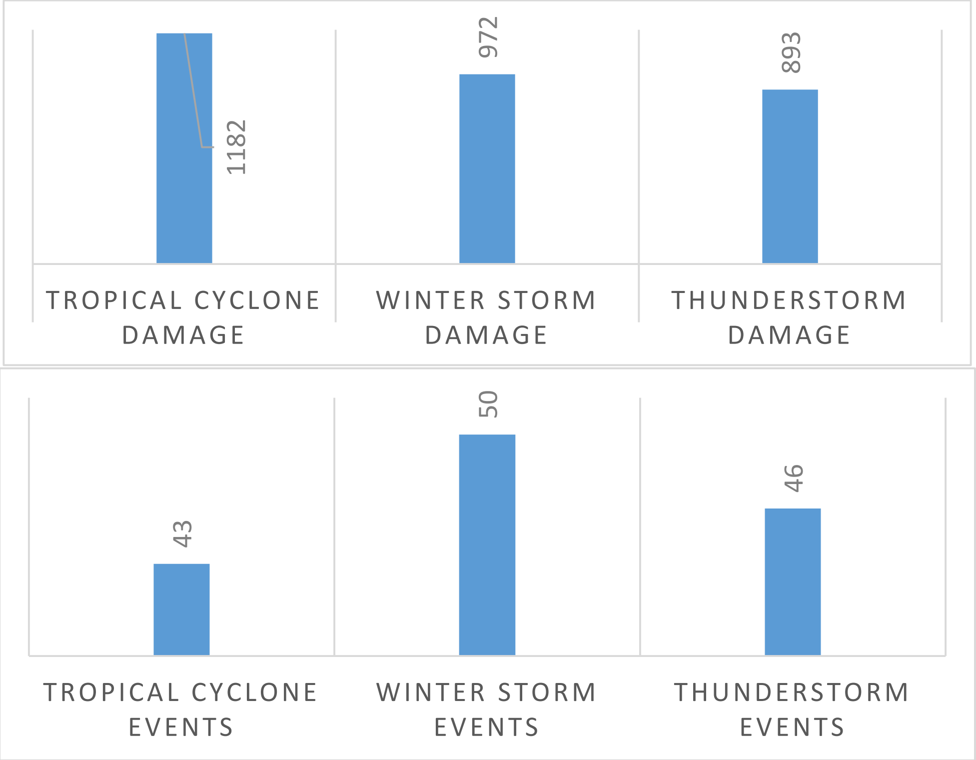

Figure 4.17: damage by cause and number of observed events during study period on pbi**.**

More winter storms were observed on PBI than thunderstorms and tropical cyclones, but tropical cyclones cause the most amount of damage (Figure 4.17). Although this study focuses primarily on the surface area change as whole and not the translocation or change of shape of any island in the study area, patterns observed on PBI mirror those observed on Ship Island prior to its permanent split into WSI and ESI. The center of the island is being hollowed out and thinning rapidly over time (Figure 4.18). On several occasions, the storm surge from hurricanes created extensive sheet wash and channel incisions. Channel incisions, like those observed on ESI and PBI following major hurricanes, are considered the most destructive storm impact on a barrier island (Morton 2008), creating narrow, elongated tracks that are closely spaced about 2 m below the water.

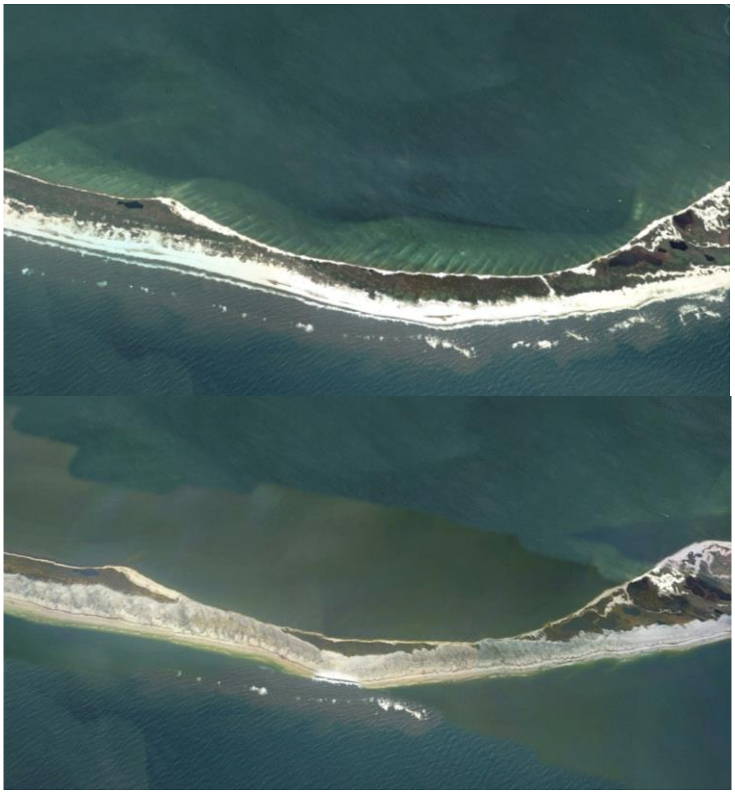

Figure 4.18 Petit Bois Island before (top) and after (bottom) Katrina. Overwash terraces on PBI as a result of sediment deposition during submursion are visible on the center of the island. Both of these secions have been thinning out on the island over time, echoing the pattern observed on Ship Island before it split into West and East.

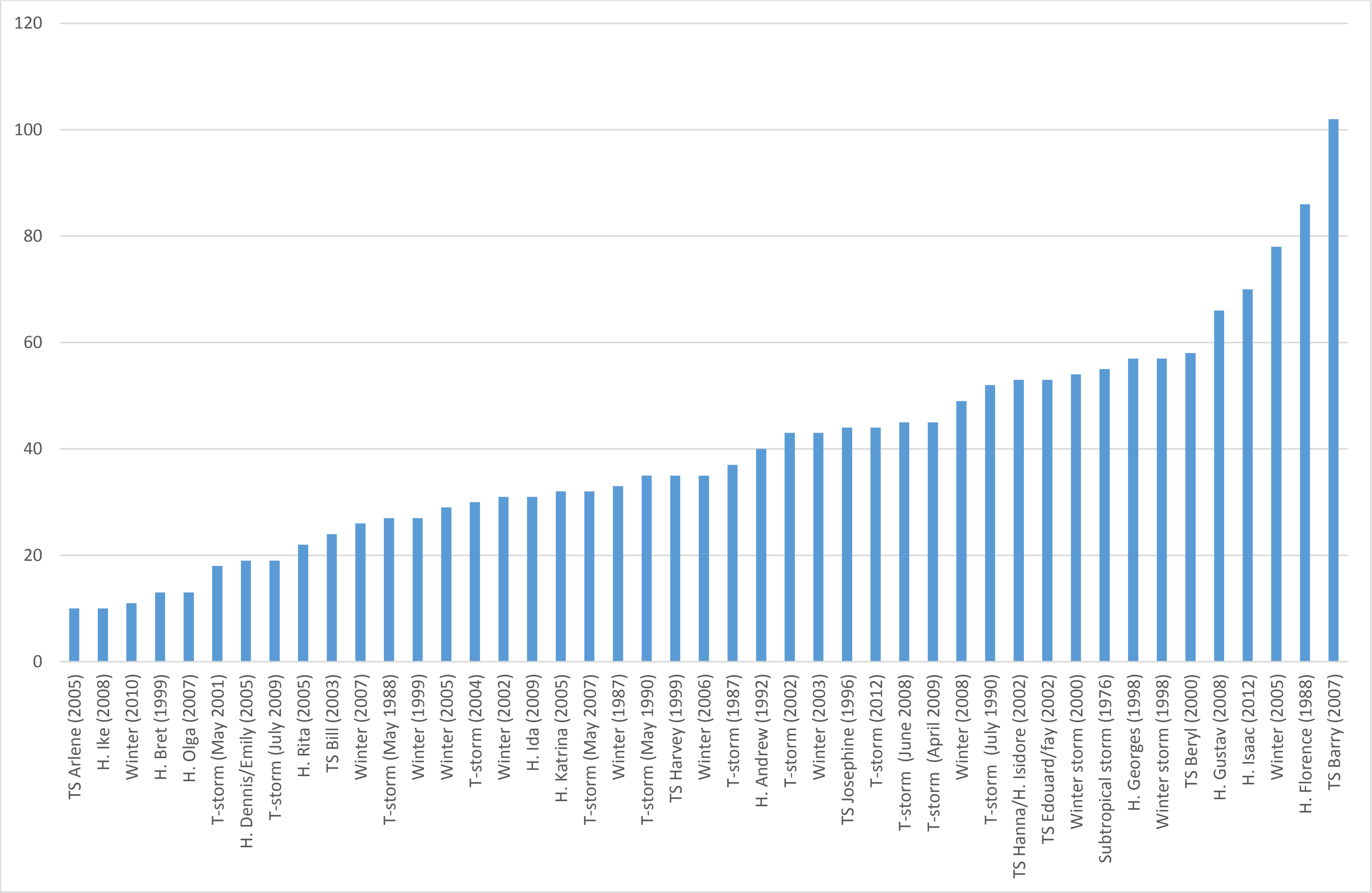

Figure 4.19 Most impactful events on Petit Bois Island by hectares (ha) eroded

4.4.a. Petit Bois Island: Period I

Data availability during Period I was limited due both to the poor temporal resolution, meaning satellites did not cover PBI as often as WSI and ESI, and due to poor spatial resolution, meaning the quality of the imagery during Period I was poor, as well. The data collected for PBI during this period shows that the island reached 700 ha during the first few years of the study period (December 1972, November 1973, December 1975, and October 1976). PBI did not dip below 600 ha until an unnamed tropical depression struck on June 12, 1977, eroding 91 ha of surface area less than two days before the next image was taken. The surface area fell below 600 ha again later that year when Hurricanes Anita and Babe struck within five days of each other, bringing the surface back down to 579 ha. Because the orbital tracks of Landsats 1-4 brought the sensors farther west than Landsat 5, placing PCI in the eastern periphery of the view, PBI may appear enlarged and distorted, which explains why these data were excluded from spatial analysis.

Table 4.9 Linear regression model results for sea level and time on Petit Bois Island during all time periods.

	Estimate	**Std.Error**	**T-Value**	**Pr(|T|)**
Intercept	6.822^{02}	1.733^{01}	39.365	2.0^{-16}
Sea Level	-4.239^{-02}	6.385^{-03}	-6.639	1.19^{-10}
Wsiarea	-1.497^{-02}	4.672^{-04}	-32.047	2.0^{-16}
R^2: 0.771	F-Statistic: 598.7			

4.4.b. Petit Bois Island: Period II

At the start of Period II, PBI measured 577 ha with seasonal fluctuations of about 30 ha from top to bottom. A severe thunderstorm in May 1985 eroded 23 ha of area. Hurricane Elena eroded 50 ha of surface area and is the first time in the study period that the island's total surface area fell below 500 ha. A strong winter storm in early February 1986 eroded 21 ha, but was not as damaging as winter storms in 1987, which eroded 70 ha of surface area. Hurricane Florence eroded

86 ha of area – the second time in the study period the island's surface area fell below 500 ha, dipping down to 471 ha. For comparison, Hurricane Katrina was the single-most erosive event in the entire study period for ESI and eroded 88 ha. The island only recovered 57 ha of the area it lost during Florence and experienced multiple back-to-back winter storms that continued to deal blows to the island – two winter storms eroded 40 ha more by the end of the year. From November 1988 through January 1989, just after Hurricane Florence made landfall as a Category 3 hurricane, the island was hit with a series of intense storms.

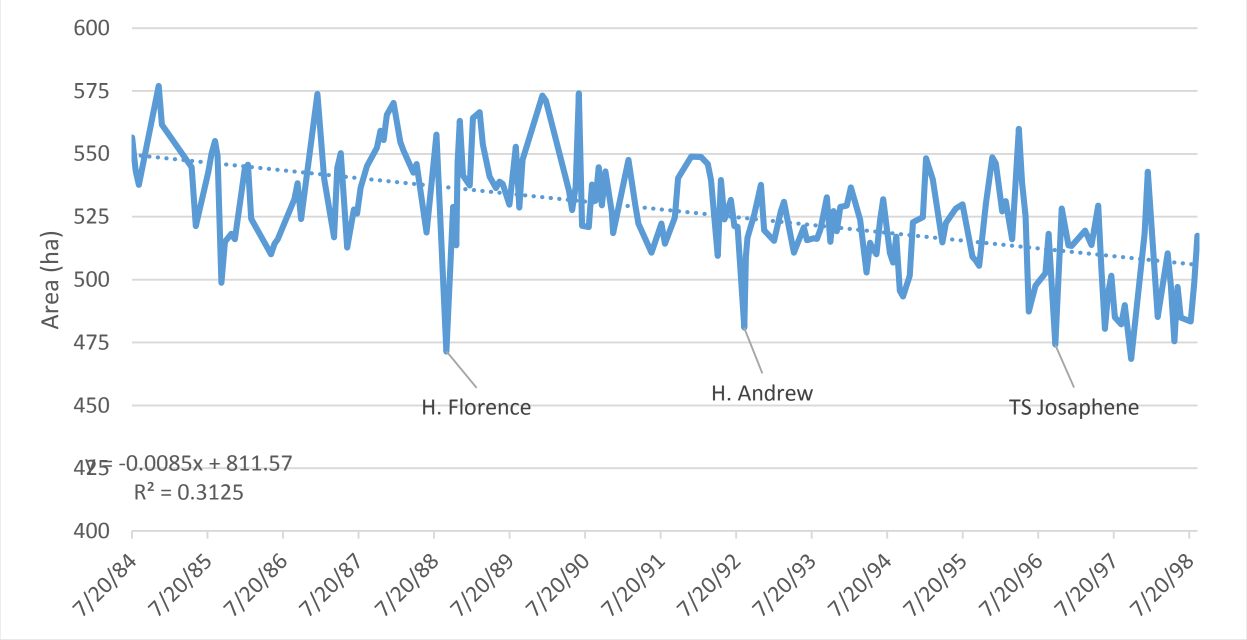

Figure 4.20 Area change on Petit Bois Island during Period II.

Thunderstorms in May and June 1990 eroded 35 and 52 ha, respectively. Winter storms that same year eroded 25 ha. An early tropical depression in June 1991 eroded 11 ha. A severe thunderstorm in April 1992 eroded 30 ha, followed by a May thunderstorm that eroded 15 ha. A July tropical depression eroded 10 ha, which was not recovered before Hurricane Andrew made landfall on August 26, 1992 and eroded 40 ha. Hurricane Andrew caused PBI to again dip below

500 ha for the third time in the study period. It would be four years before another storm would force the island below 500 ha, after which time the area often dipped below 500 ha.

By the end of 1992, severe storms and hurricanes had eroded 110 ha of surface area – more than one-fifth of PBI's total area. Strong winter storms and thunderstorms eroding anywhere between 10 and 25 ha of surface area were common for PBI, even during the extremely stable Period II. In 1993, PBI experienced two such storms: one in April and the other in October, each eroding about 20 ha of surface area. Despite these two storms, the island experienced a net gain of about 9 ha in 1993 and 116 ha of change between all of the images.

Table 4.10 Correlation analysis results from R for Petit Bois Island for all time periods.

Factor And R-Squared For PBI	**Period II**	**Period III**	**Period IV**	**ALL PERIODS**
West Ship Island Area	0.851	0.860	0.793	0.923
East Ship Island Area	0.801	0.550	0.376	0.881
Sea Level (Pensacola, Fla.)	**-0.519**	-0.147	**-0.441**	-0.308
Time Series	-0.485	**-0.794**	-0.166	**-0.894**
Days Per Month Above 32°C	-0.139	-0.488	-0.328	-0.281
Days Per Month With Min Temp Below 0°C	0.297	0.144	0.273	0.031
Extreme Maximum Monthly Temperature	-0.329	-0.398	-0.382	-0.279
Extreme Minimum Monthly Temperature	-0.317	-0.327	-0.333	-0.216
Mean Monthly Temperature	-0.383	-0.372	-0.360	-0.220
Mean Minimum Temperature	-0.392	-0.368	-0.352	-0.193
Mean Maximum Temperature	-0.370	-0.370	-0.363	-0.247
Total Monthly Precipitation	-0.163	-0.582	-0.328	-0.077
Extreme Daily Precipitation	0.070	-0.667	-0.301	-0.020

Two tropical storms struck in 1994 (Alberto and Debby), each eroding 21 ha, in addition to two winter storms that eroded 32 combined in March and April. Tropical Storm Dean was the most impactful event on PBI in 1995 and eroded 22 ha of surface area. Activity picked up in 1996 and five events caused more than 150 ha of surface area – more than all of the erosion experienced on the island caused by natural fluctuations and more than half of all fluctuations observed on PBI for that year. Comparatively, 1997 was a relatively quiet year with 88 ha of erosion caused by a combination of thunderstorms and tropical storms, accounting for only 40% of all the change observed for that year. Leading into 1998, PBI experienced two major thunderstorm events – one in February eroding 57 ha and one in April eroding 22 ha. The February thunderstorm eroded the same amount of surface area as did Hurricane Georges seven months later.

4.4.c. Petit Bois Island: Period III

Hurricane Georges put PBI in the crosshairs of its northeastern-most quadrant, where top wind speeds and storm surge occur, resulting in 57 ha of erosion for PBI. While as a single event Georges caused a lot of damage, winter storms and thunderstorms the same year eroded 93 ha of surface area, bringing the island's total surface area down to 419 ha – 100 ha smaller than less than two weeks before Hurricane Georges made landfall. Extreme events become more regular and more impactful during this period. Even hurricanes that did not come within 100 km of the study area begin appearing in the record. Hurricanes Bret, Harvey, and Hanna, for example, caused considerable damage on the island even though they made landfall nowhere near PBI. A strong winter storm in March 2000 eroded 65 ha of surface area – more than Hurricane Georges.

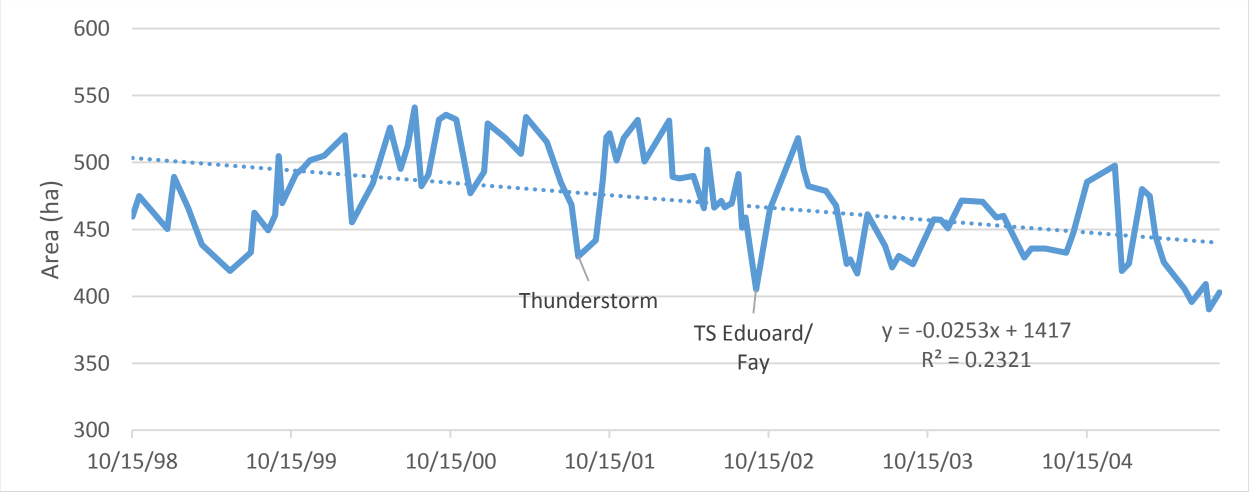

Figure 4.21 Area change on Petit Bois Island during Period III.

Tropical Storm Beryl eroded 58 ha more from PBI and a succession of winter storms in 2000-2001 eroded about 100 ha of surface area, chipping away at PBI's large surface area. During the 2001 hurricane season, Tropical Storms Allison and Barry eroded 46 and 38 ha of surface area, respectively, leaving the island at 429 ha on August 4, 2001. The island recovered nearly 100 ha by October 15, 2001, before Hurricane Michelle struck and eroded 20 ha at the end of the 2001 hurricane season.

PBI experiences the same seasonal fluctuations as WSI and ESI in that it grows most in winter, shrinks slightly in spring, grows in early summer, and shrinks slightly in fall. Winter storms on PBI are much more impactful than they are on the islands, however, eroding 139 ha in 2002 alone. Hurricanes also made a strong appearance in 1992 – Tropical Storm Bertha eroded 40 ha and Tropical Storms Hanna and Fay eroded 53 ha. Extreme events eroded 232 ha of land from PBI in 1992, totaling 57% of all the observed change on the island for that year.

Table 4.11 Sea level correlations with area on Petit Bois Island.

PBI Sea Level	**Period II**	**Period III**	**Period IV**	**ALL PERIODS**
Sea Level (Pensacola, Fla.)	-0.281	-0.178	-0.441	-0.308
Highest (Dauphin Island)	-0.178	-0.168	-0.462	-0.381
Mhhw	-0.387	-0.472	-0.553	-0.522
Mhw	-0.394	**-0.503**	-0.539	**-0.524**
Msl	-0.490	-0.320	-0.526	-0.498
Mtl	-0.481	-0.362	-0.497	-0.499
Mlw	**-0.536**	-0.200	-0.448	-0.459
Mllw	**-0.536**	-0.210	-0.487	-0.461
Lowest	-0.519	-0.038	**-0.561**	-0.356

In 2003, however, hurricanes took a back seat to a series of devastating thunderstorms that eroded 81 ha of surface area, compared to 45 ha eroded by tropical storms Bill and Henri. 2004 was relatively quiet, excluding a strong winter storm that struck in December 2004 and eroded 78 ha. Three more storms that winter would erode 57 ha more going into 2005. Tropical Storm Arlene, which struck early on in the 2005 hurricane season, only eroded 9 ha of surface area from PBI, but it was enough to make PBI reach a record low – 395 ha, the first time PBI reached below 400 ha in the entire time period. Hurricane Dennis, which did not even show up on WSI or ESI, eroded 18 ha of surface area, which was nearly fully recovered before Hurricane Katrina made landfall on August 29, 2005.

4.4.d. Petit Bois Island: Period IV

While Hurricane Katrina dealt a near-fatal blow to ESI, it only eroded 32 ha from PBI. A severe storm that hit just months after Katrina eroded 35 ha. Tropical Storm Barry (2007) was the single-most erosive event for PBI during the entire study period, eroding more than 100 ha from PBI. The lasting impact of PBI was small by comparison– about 10 ha two months after the storm, but the immediate overwash was the most severe of any hurricane observed on the island since 1972. The large amount of area eroded by Tropical Storm Barry on Petit Bois Island makes that cyclone the single-most erosive event across the island chain for the entire study period, eroding 185 ha across all four islands – 25 ha more total area than was eroded during Katrina.

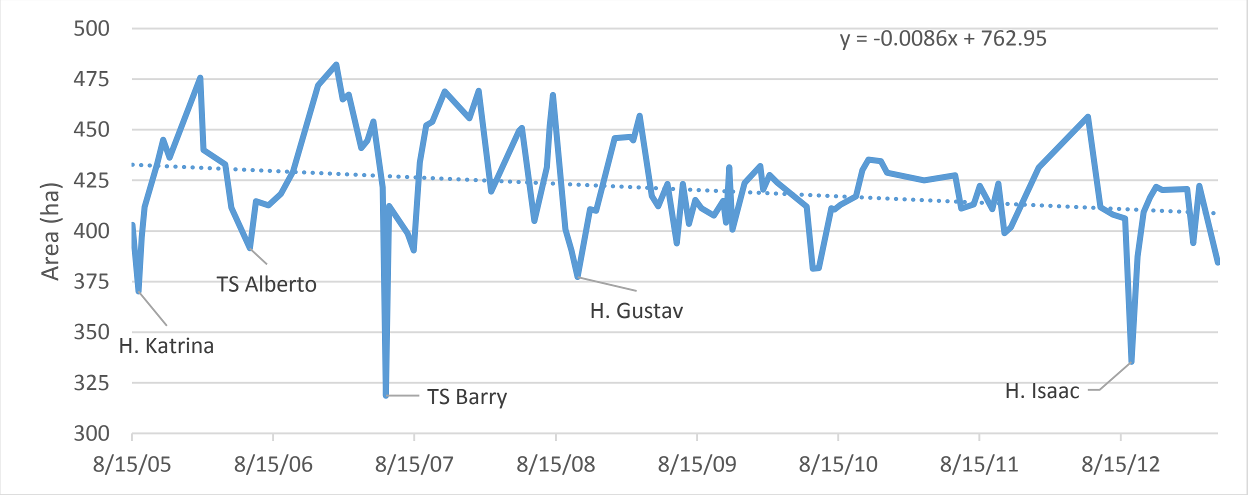

Figure 4.22 Area change on Petit Bois Island during Period IV.

Hurricane Gustav (2008) eroded more than twice the amount of area on PBI that Katrina did – about 76 ha. Hurricane Isaac (2012) eroded 70 ha of surface area from PBI, which equals the amount of erosion caused by Hurricane Gustav, or more than twice the amount of damage caused by Hurricane Katrina. Thunderstorms and tropical cyclones have become increasingly more severe on PBI with time following Hurricane Katrina, which compromised the island's dune structure and vegetation health. While Katrina may have had a smaller immediate impact and did not shave off as much surface area as Gustav or Isaac, it likely physically moved more sand on the island than the other two storms, setting the stage for future storms to easily move loose soil and un-rooted vegetation from the island.

4.5 Sand Island

Sand Island appears intermittently from 1973 through 1975. While the island reached 14 ha by November 17, 1973, it completely disappears by April 1974 and remains submerged until September 19, 1974, when it reappears at 5 ha. It disappears again in February 1975, reappears as 1.5 ha in May 1975, and then disappears again from May to October 1975, when it re-emerges as 7 ha on October 20 and steadily grows from that point forward, never being fully submerged again.

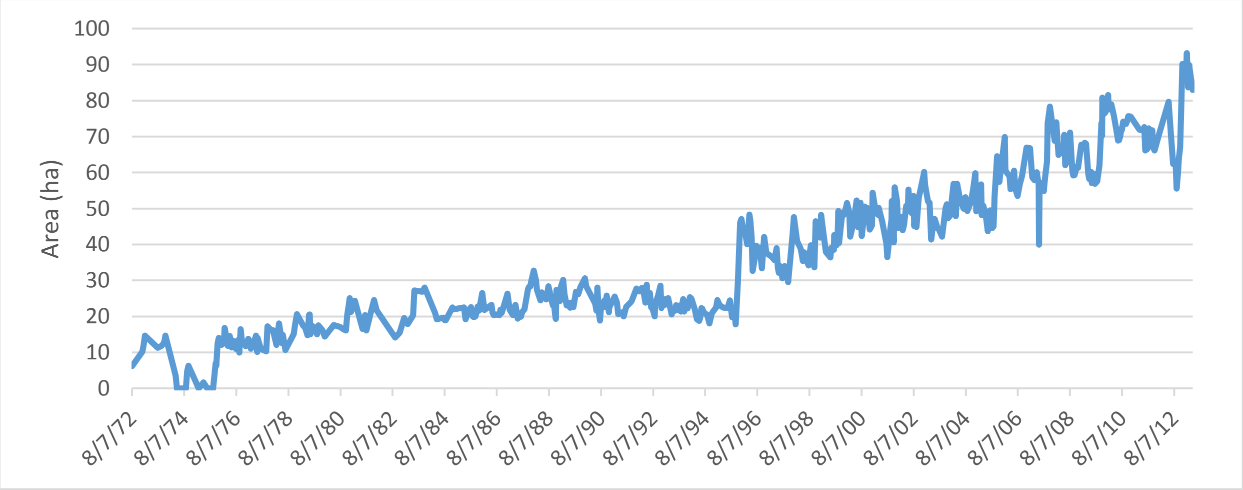

Figure 4.23 Area change on Sand Island 1972-2014.

Because Sand Island was so small during Periods I and II, finding signals for major events can be tricky. Seasonal fluctuations of 15 to 20 ha were normal on WSI, ESI, and PBI, but on Sand Island, seasonal fluctuations ranged from 2 to 7 ha during Period I. Proportional to its size this was a much greater fluctuation in area, but an overall smaller number and harder to pinpoint extreme events with. Sand Island does not follow the pattern of periods observed on the other three islands in that it was defined by only two periods: slow growth (1972-1995) and rapid growth (2014). The linear trend line from the beginning of the study period to present was 0.86 R^2, meaning linear progress of the island was a very strong predictor of growth.

Many of the dramatic losses on Sand Island are not attributable in that they do not align with either extreme weather events observed on the other islands and are not recorded in the GINS record as being part of any restoration/nourishment project. One such example is June 1981, when Sand Island lost one-third of its surface area (then 7 ha) with no known cause. The discrepancy could be caused by the different sensors being used during this time period, which may reflect some areas as being submerged in one photo, but not in another due to sensitivity to light, the time of day the image was taken, and the spatial resolution of the image. As the island becomes larger it also becomes more sensitive to extreme weather events. Of the known major events to occur across the system, the first to show up in Sand Island's record was Hurricane Georges (1998).

Hurricane Katrina resulted in a net gain of 5 ha on Sand Island. This was likely due to Sand Island's position on the western spit of PBI. Overwash from PBI would be trapped by Sand Island, adding to its total area rather than taking from it. Most of the erosion occurring on Sand Island occurred on its Gulf of Mexico side, unlike the other islands which typically eroded from the Mississippi Sound side of the islands. Hurricane Gustav eroded 10 ha of surface area. Hurricane Isaac (2012) eroded 7 ha. Events eroding more than 10 ha remain rare on Sand Island, but have become slightly more frequent during Period IV. Sand Island surpassed ESI in total area following Hurricane Katrina (2005) and continues to grow at PBI continues to decline.

Table 4.12 Correlation matrix results from R for Sand Island during all time periods.

Factor and R-Squared for Sand Island	**Period II**	**period III**	**Period IV**	**ALL PERIODS**
Petit Bois Area	0.105	0.691	0.419	-0.791
West Ship Island Area	0.106	0.800	0.591	-0.648
East Ship Island Area	0.350	0.737	0.704	-0.756
Sea Level (Pensacola, Fla.)	-0.114	-0.411	-0.146	0.151
Time Series	**0.488**	-0.326	**0.546**	**0.920**
Days Per Month Above 32^{o}C	-0.142	-0.476	-0.254	0.132
Days Per Month With Min Temp Below 0^{o}C	0.377	0.583	N/A	0.225
Extreme Maximum Monthly Temperature	-0.201	-0.633	-0.391	-0.035
Extreme Minimum Monthly Temperature	-0.312	-0.501	-0.394	-0.094
Mean Monthly Temperature	-0.260	-0.620	-0.431	-0.064
Mean Minimum Temperature	-0.251	-0.594	-0.433	-0.093
Mean Maximum Temperature	-0.268	**-0.647**	-0.424	-0.033
Total Monthly Precipitation	0.082	-0.580	-0.043	-0.034
Extreme Daily Precipitation	0.139	-0.585	-0.119	-0.065

5. RESULTS AND DISCUSSION BY EXTREME EVENT

Hurricane intensity can be measured using a variety of factors: sustained wind speeds, wind gusts, storm surge height, barometric pressure, size, duration, rainfall, etc. Although Morton (2010) determined that storm response on barrier islands was independent of storm parameters, this study found significant correlations between storm characters and net erosion. The most important factors in a storm's impact on the islands was revealed to be a combination of storm surge, wind speed and rainfall (partly a function of duration). For this reason, each of these factors has been stated in the hurricane profiles. Thunderstorms tend to produce intense rainfall over short periods of time, much like mid-latitude cyclones. Hurricanes lasted for a longer period of time and varied in terms of rainfall, but brought higher sea levels than thunderstorms and mid-latitude cyclones.

Developing an algorithm to determine relative intensity of a hurricane on a specific landscape envelopes multiple advanced climatological studies and well beyond the scope of this paper. However, a basic correlation matrix of various factors of a hurricane and loss observed on landscapes showed that minimum pressure, rainfall total, storm surge height above mean sea level, wind speed and distance of storm center from study area were all correlated with total loss (Table 5.1).

Table 5.1 Correlation between net erosion and storm parameters.

Factor:	**WSI**	**ESI**	**PBI**	**Sand Island**
Min. Pressure	-0.664	-0.266	-0.149	--
Rainfall	0.518	0.207	0.256	0.093
Storm Surge	**0.825**	--	**0.331**	**0.381**
Windspeed	0.387	**0.624**	--	--
Distance	-0.234	-0.369	-0.024	--

While some storms had wide-felt impacts across the entire island chain, some disproportionally affected each island (Figure 5.2). When considering net combined erosion for each island and each storm, Tropical Storm Barry (2007) caused the most amount of overall damage, mostly due to the severe damage caused to PBI, which generally experiences more loss per storm than the other islands. However, when the spread of damage across the system is considered, Hurricanes Katrina, Georges, Isaac, and Gustav, and Tropical Storm Barry had the greatest overall impacts. Other storms had relatively minor impacts on one island, but severe impacts on others – such as Tropical Storm Josephine which caused considerable damage on PBI, but no discernable damage on WSI or ESI.

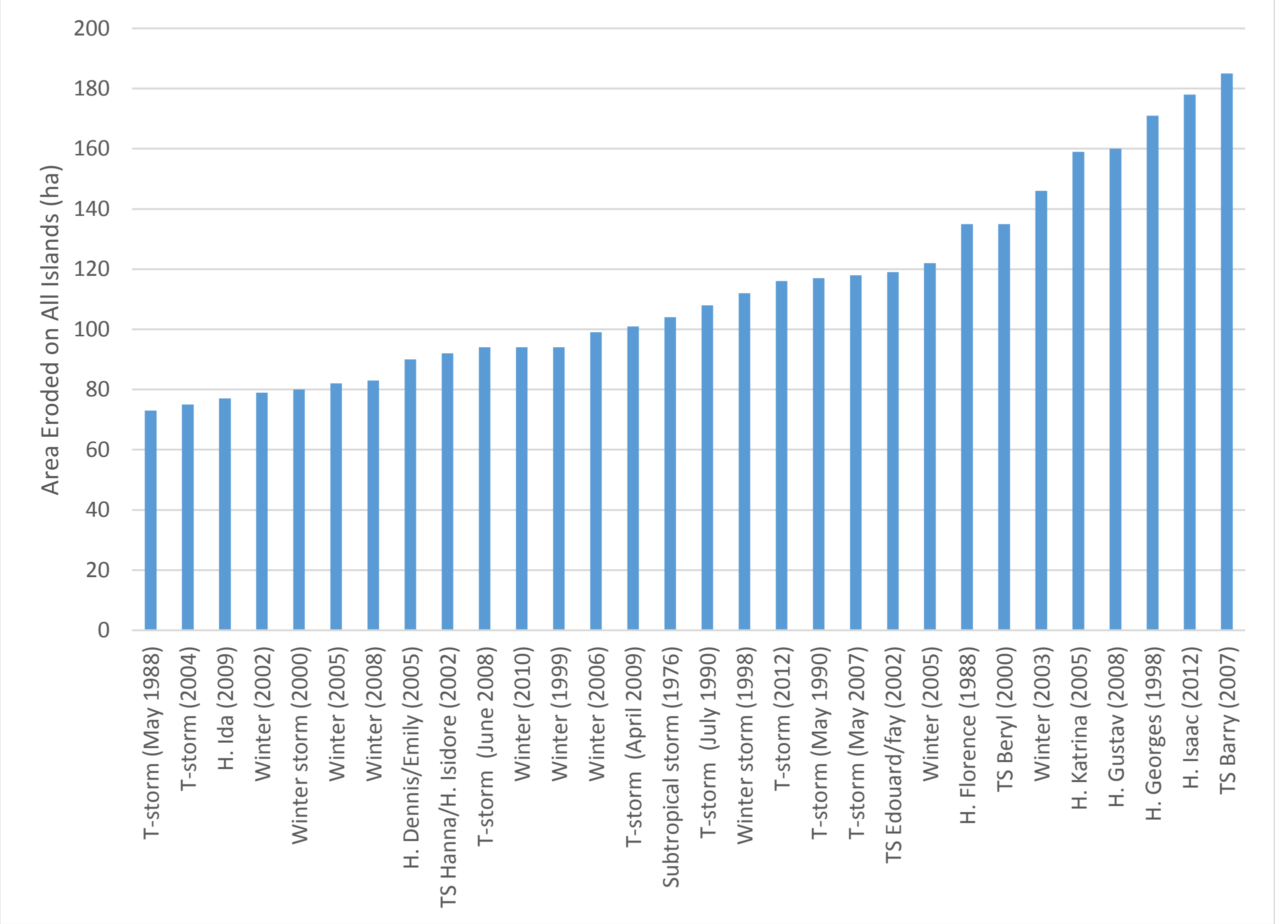

Figure 5.1 Combined damage caused by select extreme events.

5.1 Subtropical Storm Alpha, Hurricane Agnes and Hurricane Dawn (1972)

Of all the systems impact the island during the entire study period, the Alpha-Agnes-Dawn trio remains the most elusive. Three tropical cyclones struck in the first few months before and after the launch of Landsat 1 on July 23, 1972. Subtropical storm Alpha struck the Florida panhandle on May 26, Hurricane Agnes made landfall near Panama City, Florida, on June 19, and Hurricane Dawn looped around the eastern side of Florida for nine days in early September.

Even though the 1972 hurricane season was the quietest year since 1930 and Dawn was the third strongest among them, it was still the single most-impactful event on WSI during the entire study period for WSI, eroding 64 ha. The storm's center never crossed into the Gulf, staying on the eastern coastline of Florida as it migrated northward. The residual bands of Dawn, however, trailed across the Gulf and managed to do enough damage to all of the islands to show up in the record, eroding 35 ha from ESI. The 1972 season occurred during a strong El Niño year, which kept hurricane activity to a minimum, with no major hurricanes forming during the season.

Images were taken on September 12 and 29, 1972, leaving a 17-day window for damage greater than most hurricanes on the two islands. A review of weather conditions in the area during that time period revealed no anomalies aside from the change in wind speed and direction and precipitation during Dawn's passing. Both WSI and ESI fully recovered by November 12, 1972. Some of the large change could be due to changes or adjustments in the Landsat sensor after it was launched, though a loss that large and clear even on the eastern spit of WSI cannot be mistaken because of glare or slight recalibration. There were no weather-observing satellites available to document the conditions during this time and a search for evidence of other systems yielded no results.

5.2 Hurricane Elena (1985)

Hurricane Elena made landfall in Biloxi, Mississippi on September 2, 1985, as a Category 3 hurricane and a minimum pressure of 953 mb. Dauphin Island reported wind gusts of 210 km/hr, near Category 4 conditions. The hurricane brought considerable rainfall amounts (398 mm), but the real damage was caused by the 3-m storm surge and intense winds. Because of the angle the storm approached the islands, when it passed over the study area the islands would have been in the least-severe quadrants of the storm. Still, Elena washed 50 ha of surface area off PBI, though it did little damage to ESI (18 ha) and even less to WSI (5 ha). The storm would have crossed within 20 km of each of the four study islands, but the trajectory and position of the storm spared WSI and ESI from its brute force, despite its slow-moving center. While not as infamous as later storms, Elena wreaked havoc on the Mississippi Gulf Coast to the point that some residents said it was worse than Frederic and Camille. Elena eroded up to 40% of the Chandelier Islands total land mass (USGS 2009). Tropical storm Juan passed through the area two months later with winds exceeding 100 mph and caused additional erosion of about 8 ha.

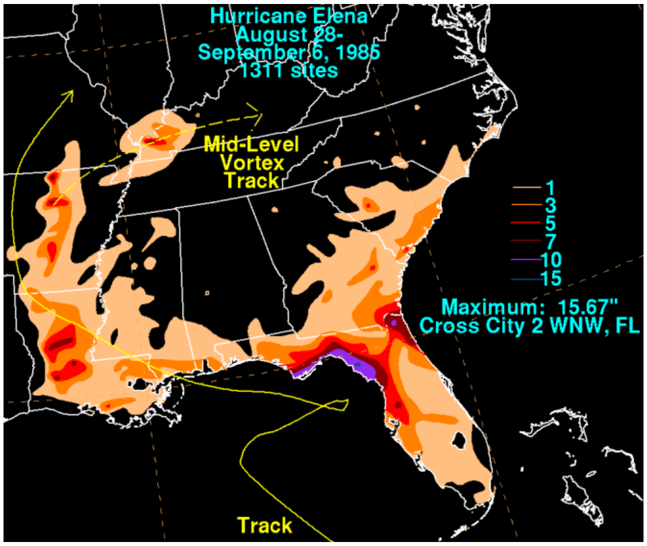

Figure 5.2 The track of Hurricane Elena and rainfall densities.

5.3 Hurricane Florence (1988)

Hurricane Florence struck near New Orleans, Louisiana, with sustained winds of 130 km/hr on September 10, 1988, putting the entire study area in the more-intense north-east quadrant of the storm. East of New Orleans on the Bayou Bienvenue (about 90 km west of the study area), a storm surge upward of 2.3 m above mean sea level destroyed key infrastructure along the coastline. Although rainfall stayed under 300 mm across the region, wind gusts peaking at 105 km/hr inland downed trees and caused multiple tornadoes. On Grand Isle, Louisiana, the U.S. Coast Guard reported losses of about 12 m of beachfront. WSI lost 17 ha, ESI 22 ha, PBI 86 ha, and Sand Island 4 ha. The data recorded before Florence was taken on July 31, 1988 – nearly six weeks before the storm’s landfall. The first image taken after the storm was taken on September 17, 1988, one week after Florence made landfall. Tropical Storm Beryl also made landfall during this time span on August 10, 1988, near Lake Pontchartrain, though its impacts were localized to the southwestern Louisiana region.

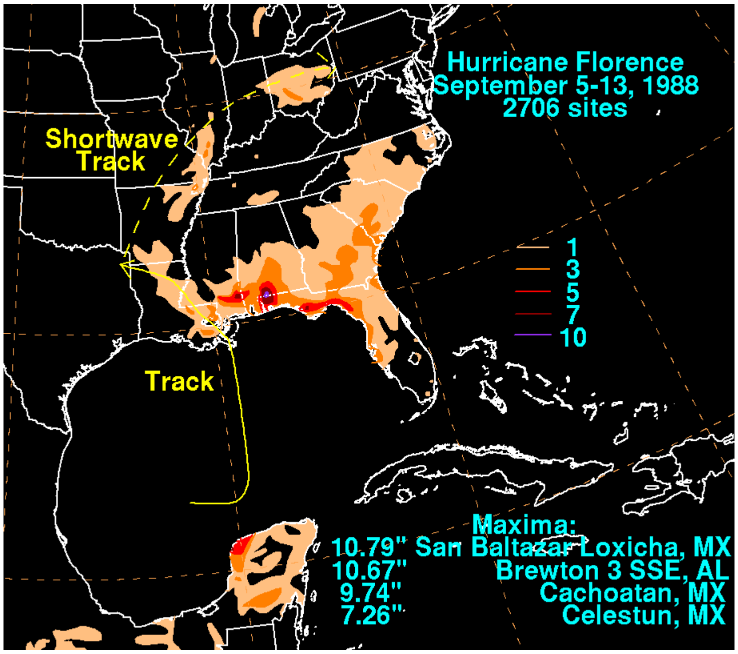

Figure 5.3 Track of Hurricane Florence and rainfall density.

5.4 Winter-Spring 1990

A succession of thunderstorms in May 1990 eroded 38 ha from WSI, 44 ha from ESI, 42 ha from PBI, and 5 ha from Sand Island. Landsat 4-5 data were unavailable between January 10 and April 16, 1990, making three months of change unmonitored. Part of the loss could be due to sea level rise and natural seasonal variability, but the significant losses between May 2 and May 18, 1990 appear to largely be the result of a series of severe thunderstorms. Weather-monitoring radar for this time period was unavailable, but record from the National Climate Data Center reflect a system moving through on May 9-10, 1990 with barometric pressure dropping to 1008 mb with wind gusts upward of 40 km/hr. Other storms in April may have caused loss, as well – a storm system on April 28 brought wind gusts of 56 km/hr and a minimum pressure of 1003 mb. Storms on March 14, 16-17, and 19-20 with wind opposite wind directions and gusts up to 50 km/hr (min. pressure 1009 mb) could have been part of a mid-latitude cyclone forming over the Midwest or a squall line associated with thunderstorms across the southeast. With limited Landsat imagery and no radar data available, attribution of damage during this time period was confined to the May thunderstorm, although other storms likely caused damage earlier in the spring.

5.5 Hurricane Andrew (1992)

Hurricane Andrew struck just outside of Morgan City, Louisiana, on August 26 as a Category 3 with 185 km/hr sustained winds and a 2.4 m storm surge. ESI data during the 1992 hurricane season was somewhat limited, with a considerable gap between July 26 and September 12. The other three islands had images taken on August 27, 1992 – one day after Andrew made landfall, maximizing the visual impact of the hurricane on the islands. Hurricane Andrew eroded 40 ha from PBI, 23 ha from WSI, and 2 ha from Sand Island. ESI shows a net gain of 2 ha on September 12, two weeks after Andrew crossed its path. Andrew likely caused erosion on the island, but the loss was recovered by the time the image was taken. If ESI loss patterns match closely to WSI, the island likely lost upwards of 25 ha, although without additional data that is pure speculation. Hurricane Andrew was the fourth costliest and fourth most-intense hurricane ever to make landfall on U.S. soil as of March 2014, costing more than $26 billion and a minimum central pressure of 922 mb, respectively. In Mississippi, Andrew caused at least 26 tornadoes, 16 severe floods and maximum observed rainfall of 236 mm. The Gulf Island National Seashore staff reported beachfront losses of up to 9m on Dauphin Island.

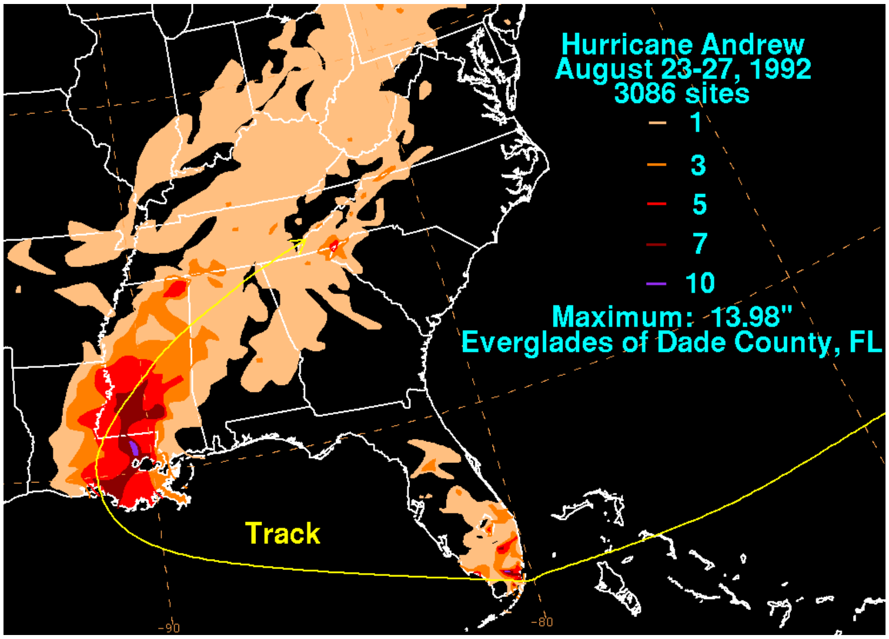

Figure 5.4 Track of Hurricane Andrew and rainfall density.

5.6 Tropical Storm Josephine (1996)

Tropical Storm Josephine approached the study area from the southwest Gulf of Mexico on October 6, 1996, with 110 km/hr sustained winds and a 2.8 m storm surge. Unlike most of the storms which hit the study area, Josephine formed over the Bay of Campeche in the southwestern area of the Gulf of Mexico and moved north-northeast across the Gulf. Josephine made landfall in Taylor County, Florida on October 8, spawning 16 tornadoes and dropping 290 mm of rain.

Josephine eroded 44 ha of surface area from PBI and 6 ha from Sand Island. Images for WSI and ESI were not taken until one-month after Josephine made landfall, on November 10, 1996 and showed net gains of 19 and 11 ha, respectively, which are consistent with the seasonal fluctuations observed throughout Period II. Because of the structure of WSI, with a rounded-spit on the western edge where storm surge would have been greatest given the direction of the tropical storm, damage may have been minimal on the Gulf side of the island.

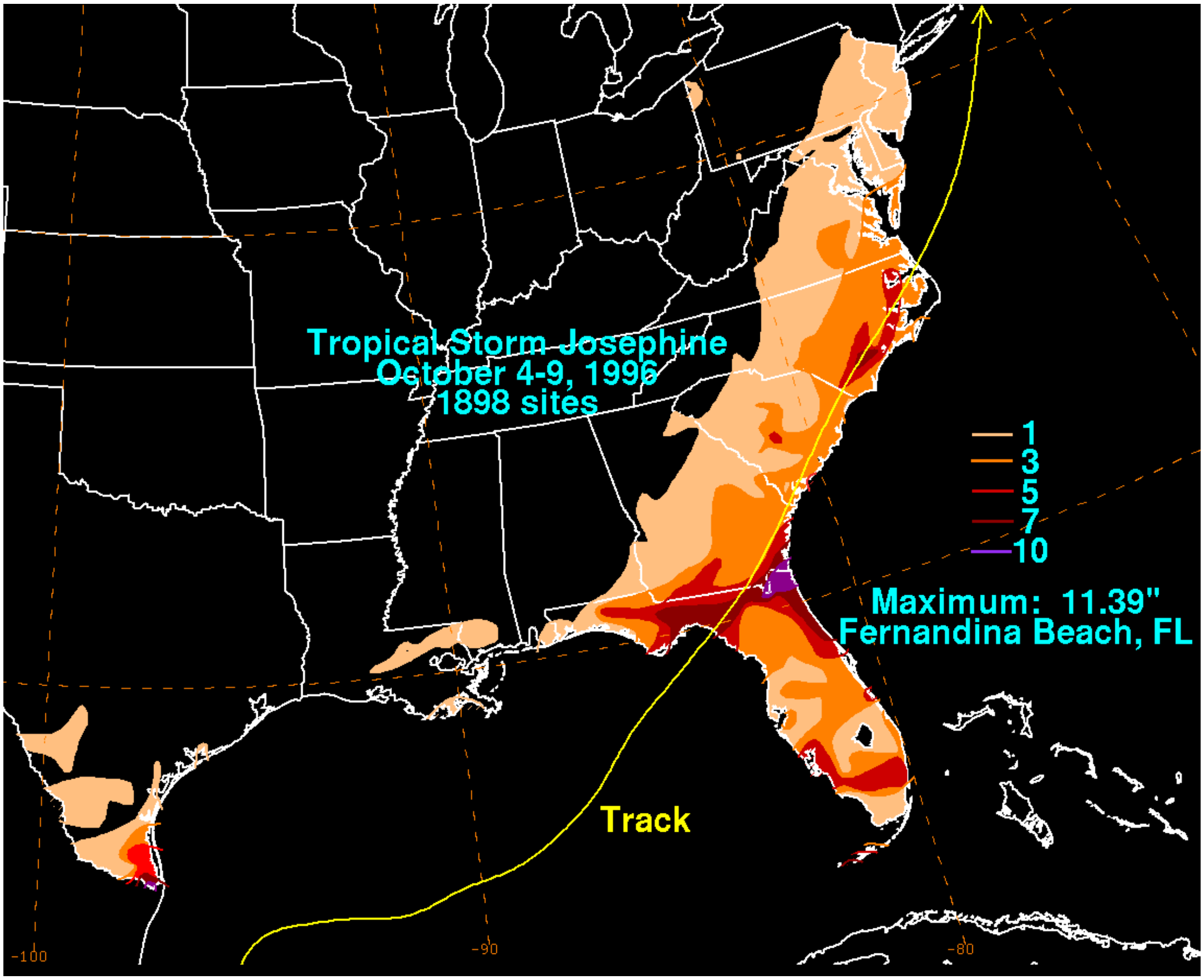

Figure 5.5 Track of Tropical Storm Josephine and rainfall density.

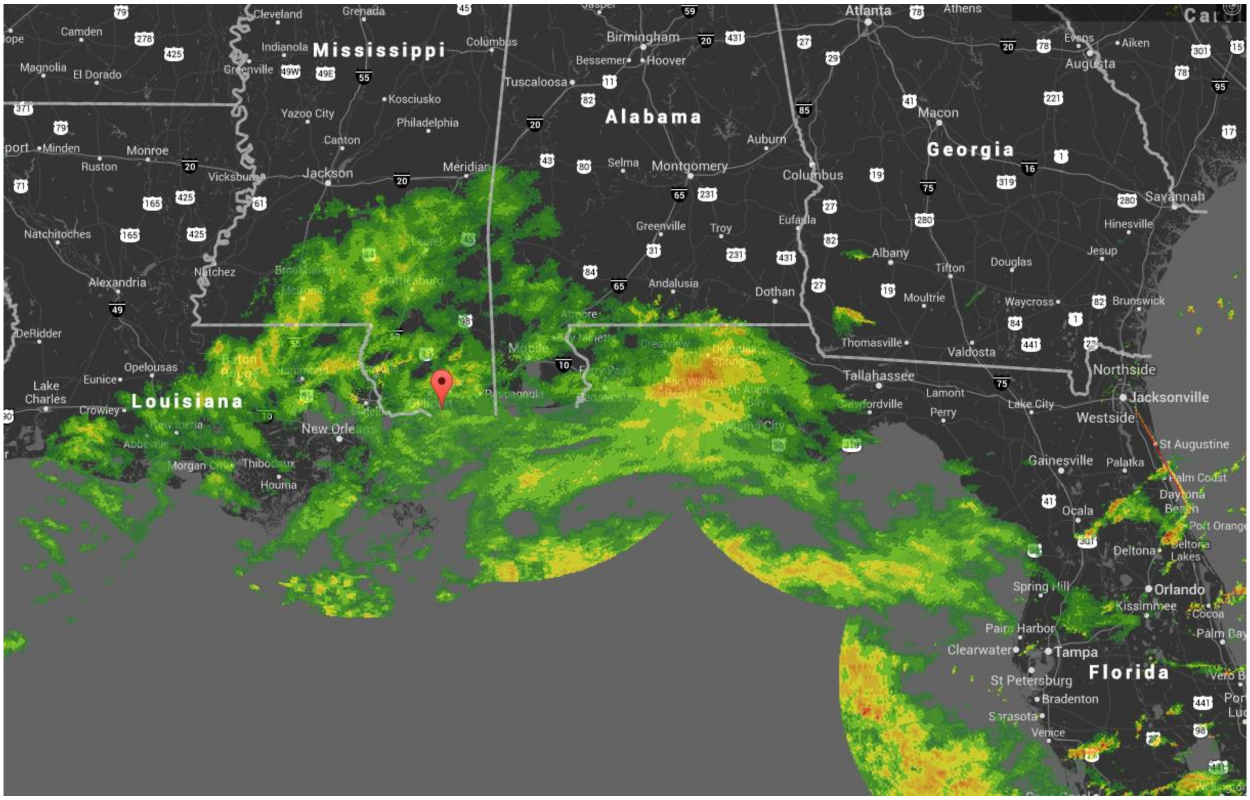

Figure 5.6 Radar image of Tropical Storm Josephine taken October 7, 1996.

5.7 Winter Storms of 1997-1998

A six-week gap in data allows a lot of room for erosion, making it difficult to attribute large losses to single events. No usable images were taken between December 31, 1997 and February 17, 1998. A strong storm lowered pressure to 998 mb and strong northerly winds with gusts up to 48 km/hr were observed in Gulfport, Mississippi on January 7-8, 1998. A second severe storm with northerly winds brought barometric pressure down to 1000 mb with wind gusts of 65 km/hr on February 1-5, 1998 (Figure 5.7). January and February were not particularly cold months, with only one day dropping below freezing. The storm eroded 27 ha from WSI, 22 ha from ESI, 57 ha from PBI, and 6 ha from Sand Island.

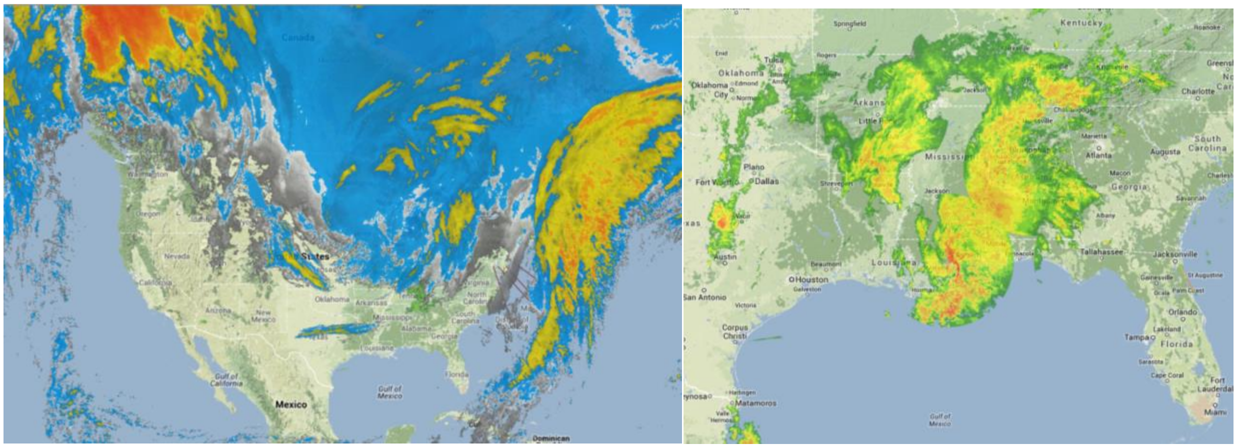

Figure 5.7 Satellite images of two winter systems moving through the study area on December 31, 1997 (left) and January 7, 1998 (right).

5.8 Hurricane Georges

Hurricane Georges struck the Mississippi coast on September 28, 1998 with 198 km/hr winds and a 2.7 m storm surge at Gulfport Beach, Mississippi. The track brought the hurricane from the southeast into the Mississippi Sound directly over ESI with a minimum pressure of 937 mb – one of the lowest of any storm to hit the area. The hurricane dumped 420 mm of rain over Pascagoula, Mississippi, with reports of rainfall exceeding 650 mm in parts of Alabama and Florida. Its slow-moving and wide structure, along with its northwesterly track, allowed the storm to be extremely erosive, even for a Category 2. Georges was the second-most erosive event on ESI during the study period. For WSI, it was the ninth most-erosive event. The cumulative damage across all four islands was 171 ha, making it the overall third most-erosive event during the study period.

Hurricane Georges immediately eroded large swaths of land on each of the islands: 72.4 ha on ESI, 58.9 ha on PBI, 35.1 ha on WSI, and 6.1 ha on Sand Island. Georges reworked the interior dunes on PBI and created washover terraces across the island. ESI was completely submerged and all but its triangular center portion were covered by washover terraces. A thinner terrace formed on WSI.

The image taken before Hurricane Georges struck was taken on August 28, 1998 – more than a month before the storm made landfall. The first image collected after the storm made landfall was taken October 15, 1998 – about two weeks after landfall. From June 9 – August 28 the islands all experienced gradual growth consistent with the seasonal pattern observed during years without hurricanes. Because the islands generally grow during the late summer months and no tropical storms struck between August 28 and September 30, it is a reasonable presumption that the islands would have been about the same size as, if not larger than, the August 28 measurement.

The recovery time following Hurricane Georges lasted four months for WSI and ESI, and more than a year for PBI – the island would not reach its August 1998 size again until January 2000. Sand Island experienced a net gain from Hurricane Georges, retaining sediment washed away from PBI. Following Georges, variability increased significantly – from 142.06 during Period II to 292.27 during Period III.

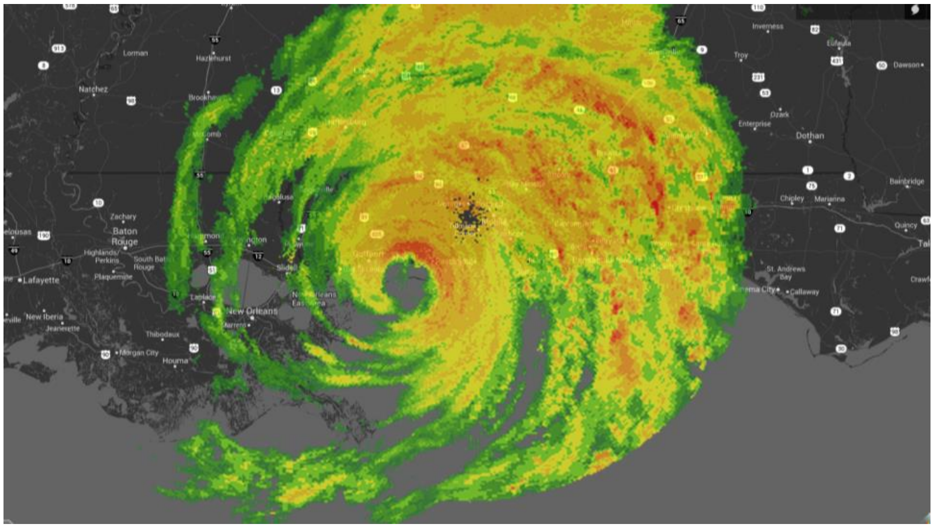

Figure 5.8 Radar image of Hurricane Georges on September 27, 1998.

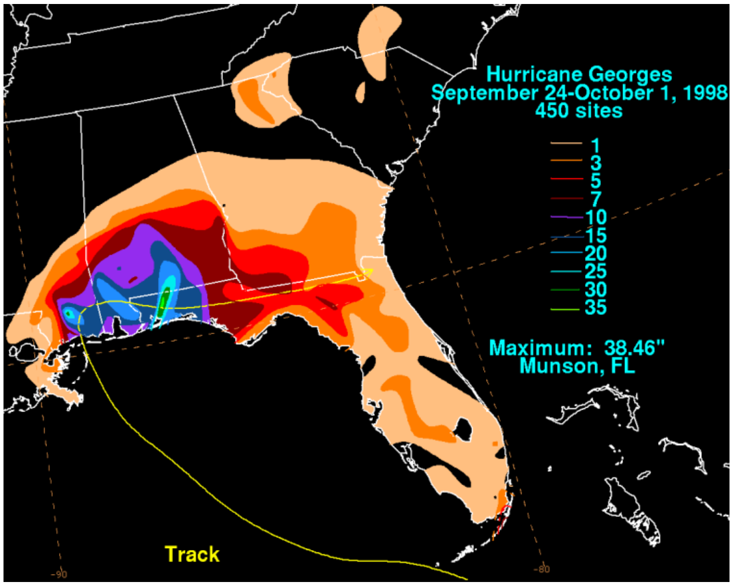

Figure 5.9 Track of Hurricane Georges and rainfall densities.

5.9 Hurricane Isidore (2002)

Hurricane Isidore made landfall on Grand Isle, Louisiana on September 26, 2002, as a strong Category 3 hurricane with 201 km/hr winds, a minimum pressure of 934 mb and a storm surge of 2.5 m. The path of storm brought it northward toward Lake Pontchartrain, about 60 km west of WSI. Maximum observed rainfall during Isidore was 762 mm in Metairie, Louisiana. Pressure reached 985 mb on September 26 with wind gusts upward of 205 km/hr and 203 mm of rainfall falling in a 12-hour period. Isidore eroded 41 ha from WSI, 55 ha from ESI, 53 ha from PBI and 8 ha from Sand Island. Hurricane Lili struck Louisiana as Category 1 storm on October 4. While no severe erosion was observed on WSI, the island did not regain more than 2 ha before a succession of winter storms hit the following winter. Unlike most years during the study period, which saw considerable growth averaging 30 ha per island during the winter months, no winter growth was observed during the 2002-2003 winter, in part due to back-to-back storms Isidore and Lili, and the severe low pressure systems that followed.

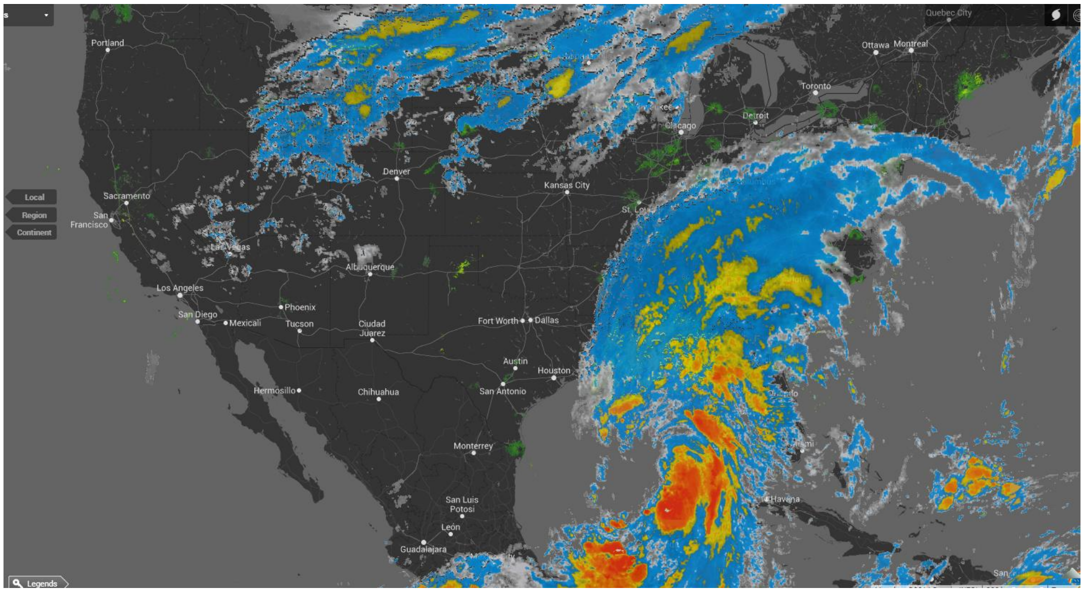

Figure 5.10 A satellite image of Hurricane Isidore taken on September 25, 2002.

5.10 Winter Storm of 2002-2003

There were nine days below freezing in January 2003, with temperatures on January 24 reaching -7°C. For the entire month of January, Gulfport only received 0.5 mm of rain, though wind gusts on January 16 reached 65 km/hr. By contrast, in December 2002 Gulfport received 170 mm of rain. A severe thunderstorm on December 31, 2002 dumped 60 mm of rain on the island in less than three hours, causing flash flooding across the coast. Wind gusts during the storm peaked at 59 km/hr, with sustained winds of 25 km/hr for up to four hours.

This particular storm eroded 11 ha from ESI, 30 ha from WSI, 23 ha from PBI, and 20 ha from Sand Island. Another thunderstorm that hit between March 24 and April 12, 2003, eroded 15 ha from WSI, 38 ha from ESI, and 43 ha from PBI. In both of these storms, none of the island fully recovered until almost a year later, the pace of recovery being much slower than after hurricanes. What causes erosion during a thunderstorm – strong winds and heavy rains on the heels of extreme cold – differs from what causes erosion during a hurricane – storm surge, winds and rain. The lack of storm surge during thunderstorms and winter systems may result in slower recovery time, since no sand was moving toward the island, unlike during a hurricane which can result in a net gain on the islands.

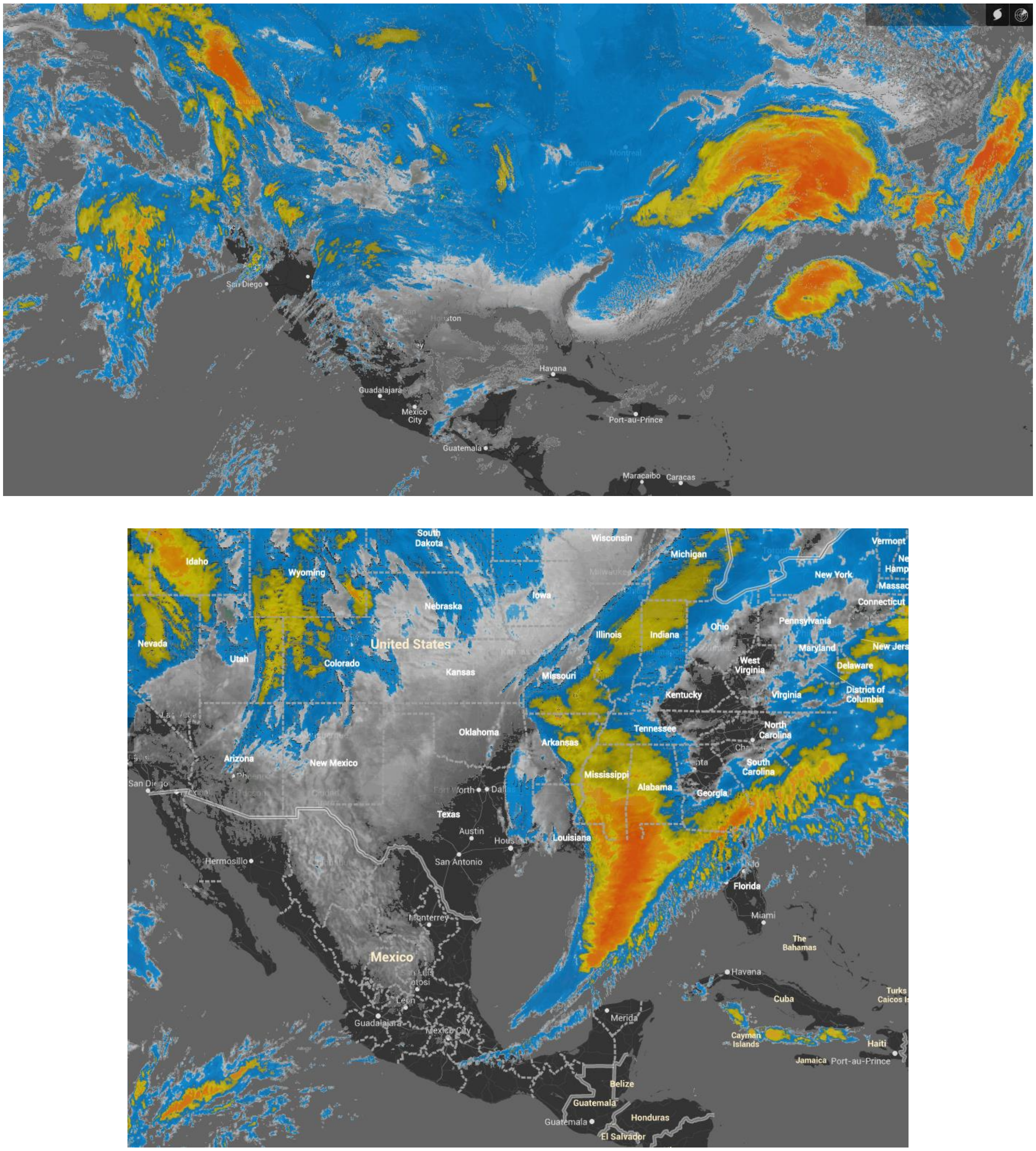

Figure 5.11 Radar image of December 31, 2002, (top) and January 24, 2003, (bottom) showing a cold front and possible mid-latitude cyclone.

5.11 Winter Storm of 2004-2005

December 2004 was a cold month for the U.S. Southeast – Gulfport experienced three straight days of below-freezing temperatures one week, then another seven below-freezing days throughout the rest of the month. In all, there were 10 freezing days in Gulfport in December 2004. In contrast, there were only two freezing days in all of January 2005, but heavy rains and winds may have been able to move soil loosened by the plant-killing freezes the previous month. Two storm systems brought maximum wind gusts of 65 km/hr and minimum pressure of 1002 mb.

5.12 Hurricane Katrina

Hurricane Katrina made two landfalls on August 29, 2005: the first with sustained winds of 205 km/hr near Buras-Triumph, Louisiana, then again later that day across the Breton Sound near the Louisiana-Mississippi border as a Category 3. The minimum pressure at the storm's eye was 920 mb and rainfall peaked at 403 mm. Hurricane Katrina made its second landfall 58 km west of the westernmost end of WSI on August 29, 2005, with Category 3 winds. The observed storm surge on WSI was 9.1 m – more than three times the storm surge height of Hurricane Georges, inundating the entire island for a prolonged period of time (Fritz et al. 2007). The observed maximum storm surge on ESI was 8 m. On PBI, the maximum observed storm surge was 4.4 m. Otvos and Carter (2008) determined, "compared to earlier cyclones, Katrina's sand dispersal from the eroded islands over the adjacent sea floor was the most extensive," and that reworked sands contributed to fast ridge reemergence. While loss of surface area was significant during Katrina, loss of vegetation was even greater – ESI lost 100% of its pine forest vegetation (Otvos and Carter 2008).

WSI lost 40 ha of surface area between August 23 and August 31, 2005, as a result of Hurricane Katrina. The island started to regain surface area between August 31 and September 16, 2005, gaining back 8 ha of lost surface area before Hurricane Rita struck on September 25, 2005, eroding 20 ha more from WSI. The island rebounded quickly, however, reaching its pre-Katrina total area by February 7, 2006.

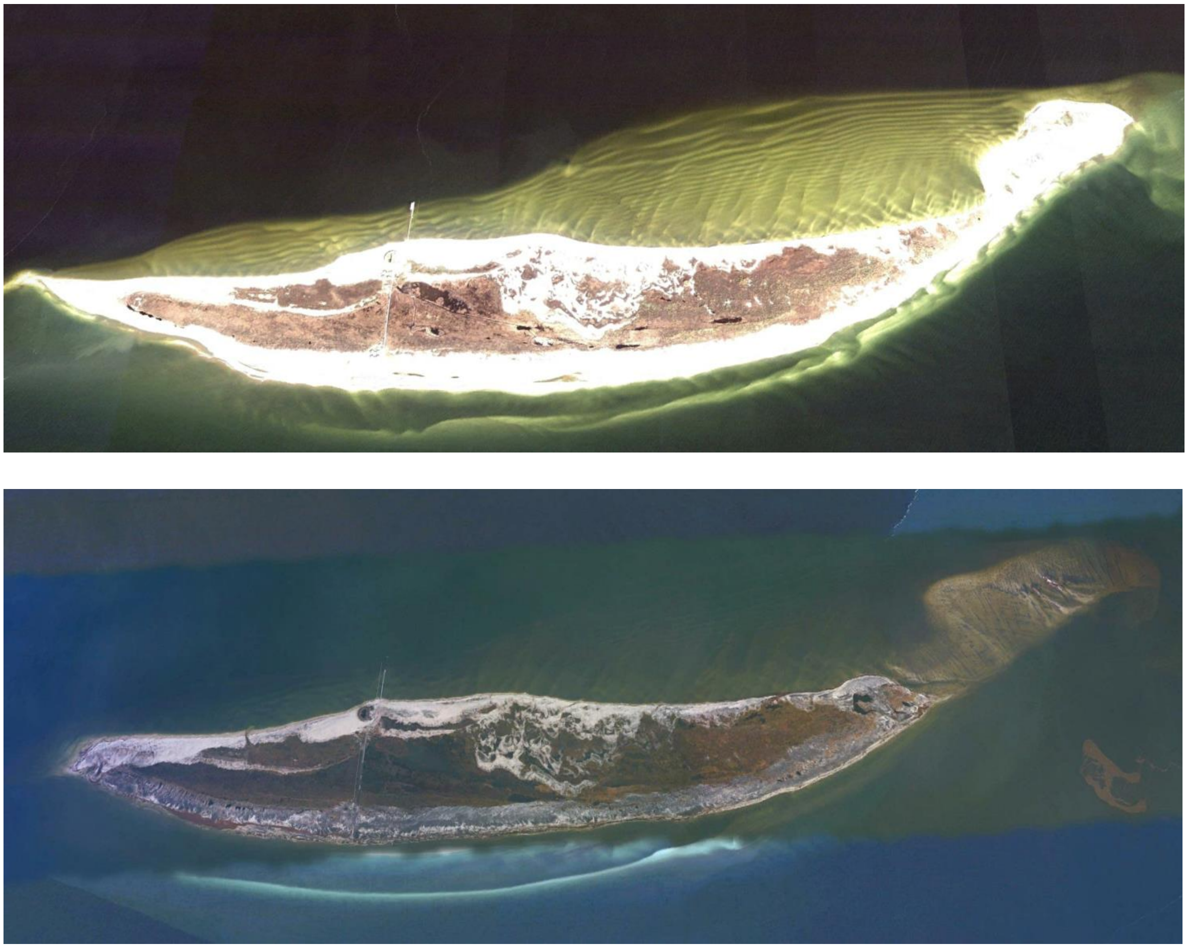

Figure 5.12 Destruction on West Ship Island caused by Hurricane Katrina. Top: March 2005. Bottom: October 2005. Overwash terraces and perched fans are visible on the southern side of the island. A large incision was cut on the eastern spit of the island.

The impact of Katrina of ESI was far worse. Katrina immediately washed away more than 88 ha of surface area – 68% of the island's surface area before the storm struck. Reports from aircraft flown over the island on September 1, 2005, stated that the island was entirely submerged – the aircraft could not find ESI on its initial pass. ESI made no recovery between Katrina and Rita, losing another 7 ha after the latter made landfall. However, the island made considerable progress during the 2005 winter, gaining about 40 ha by December 29, 2005. The gain was temporary, however, and the island lost 20 more ha between February 7, 2006 and February 15, 2006, during a strong winter storm. While ESI has been steadily growing since Katrina's 2005 landfall, it has yet to reach its 2005 size.

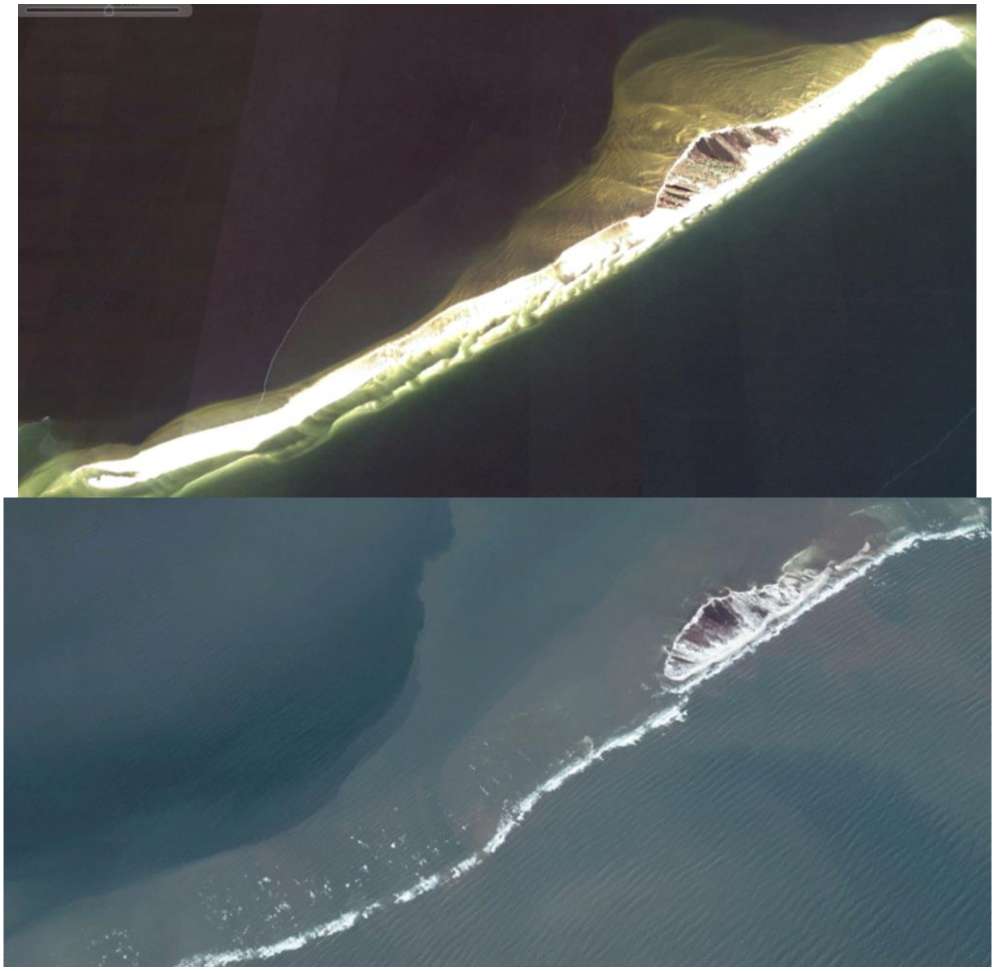

Figure 5.13 East Ship Island before (top) and after (bottom) Hurricane Katrina.

Hurricane Katrina was a devastating event for all of the islands and nearly fatal for ESI in particular. While Katrina may not have been the most devastating storm in the record for WSI, PBI, and Sand Island, the storm may have moved more surface area in the three-dimensional sense than any hurricane before or afterward. A storm's impact can depend largely on not only the storm surge, but the health of the island at the time the storm struck. For example, if a strong Category 3 hurricane destroys the foredune on an island and submerges the vegetation long enough to compromise its stability, a tropical depression that strikes a month later could have a larger impact on the island in the two-dimensional sense than the Category 3. Because of the record storm surge observed on Ship Island during Hurricane Katrina, which may have submerged the entire island for up to 12 hours, it is reasonable to assume that Katrina was such a storm, destroying the protective structures on the island so that future storms of lesser strength, like Gustav, Lee, and Isaac, could erode more surface area than Katrina initially did.

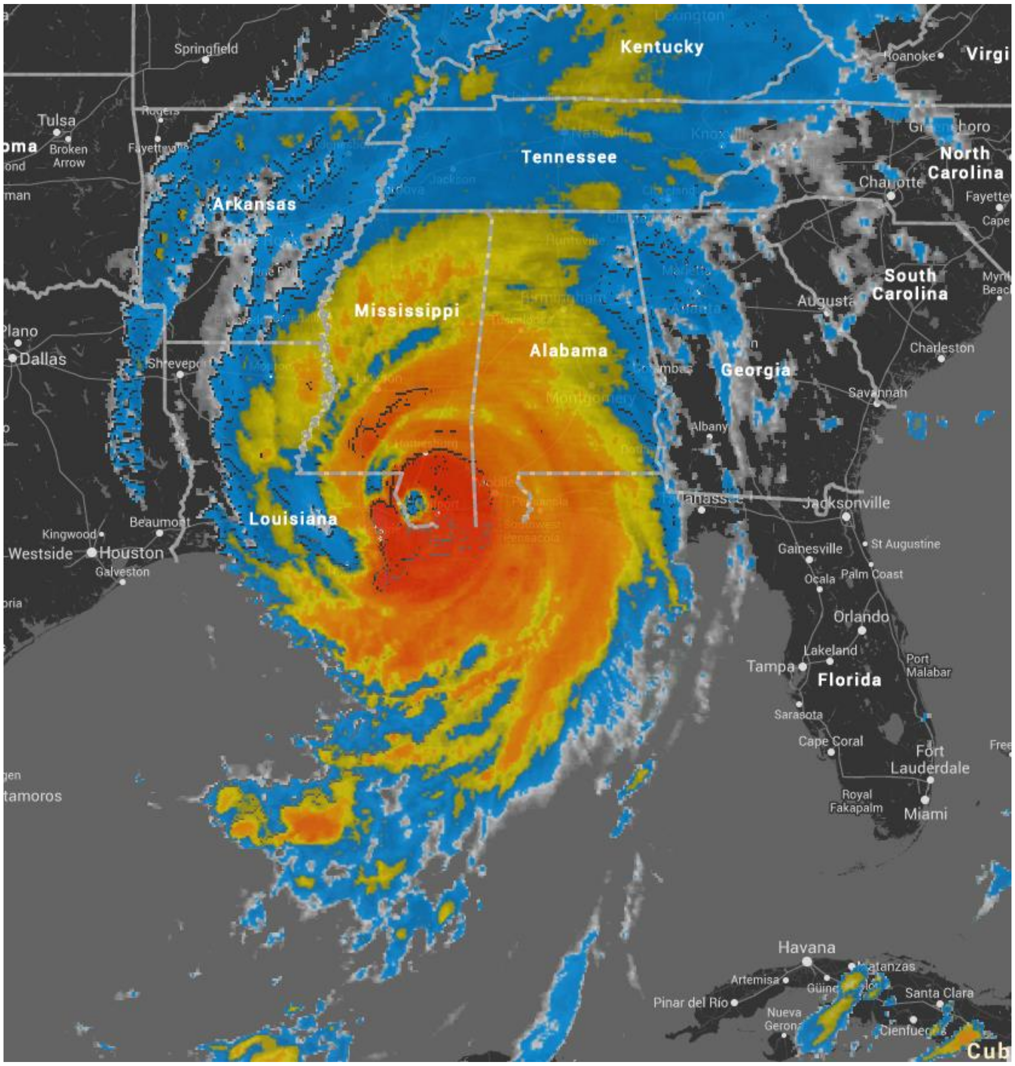

Figure 5.14 Radar image of wind speed of Hurricane Katrina.

5.13 Tropical Storm Barry

On May 25, 2007, growth of all of the islands was beginning to decelerate, but an event between May 25 and June 2, 2007, would set back each of the islands considerably, much earlier in the summer than usual. The only event occurring in proximity to the study area during this time period was Tropical Storm Barry, a very large but weak system that moved eastward across the northern Gulf Coast, striking the Florida coast on June 1, 2007. The storm formed from a trough of low pressure, gained traction, hit, and dissipated in less than 48 hours. Gulfport, Mississippi, only received 178 mm of rain from Barry, according to the National Weather Service, and barely registered in terms of drop in barometric pressure, increase in wind speed and change in wind direction.

In Mobile, Alabama, however, the barometric pressure dropped below 1006 mb and wind direction shifted significantly, indicating that a strong low-pressure system had moved through during that time. At best, the storm grazed by the system, not making a direct impact, and not leaving much of an atmospheric mark behind. Tropical Storm Barry, or any other event that could have eroded more 100 ha from PBI within a week's time, remains the only unexplained phenomena occurring in this study period. It may simply be the case that the island chain was weak from a hard beating by an extremely active 2005 hurricane season, or that the early landfall of Barry compounded with Katrina and Rita's impacts proved too much for recovering beach front and vegetation.

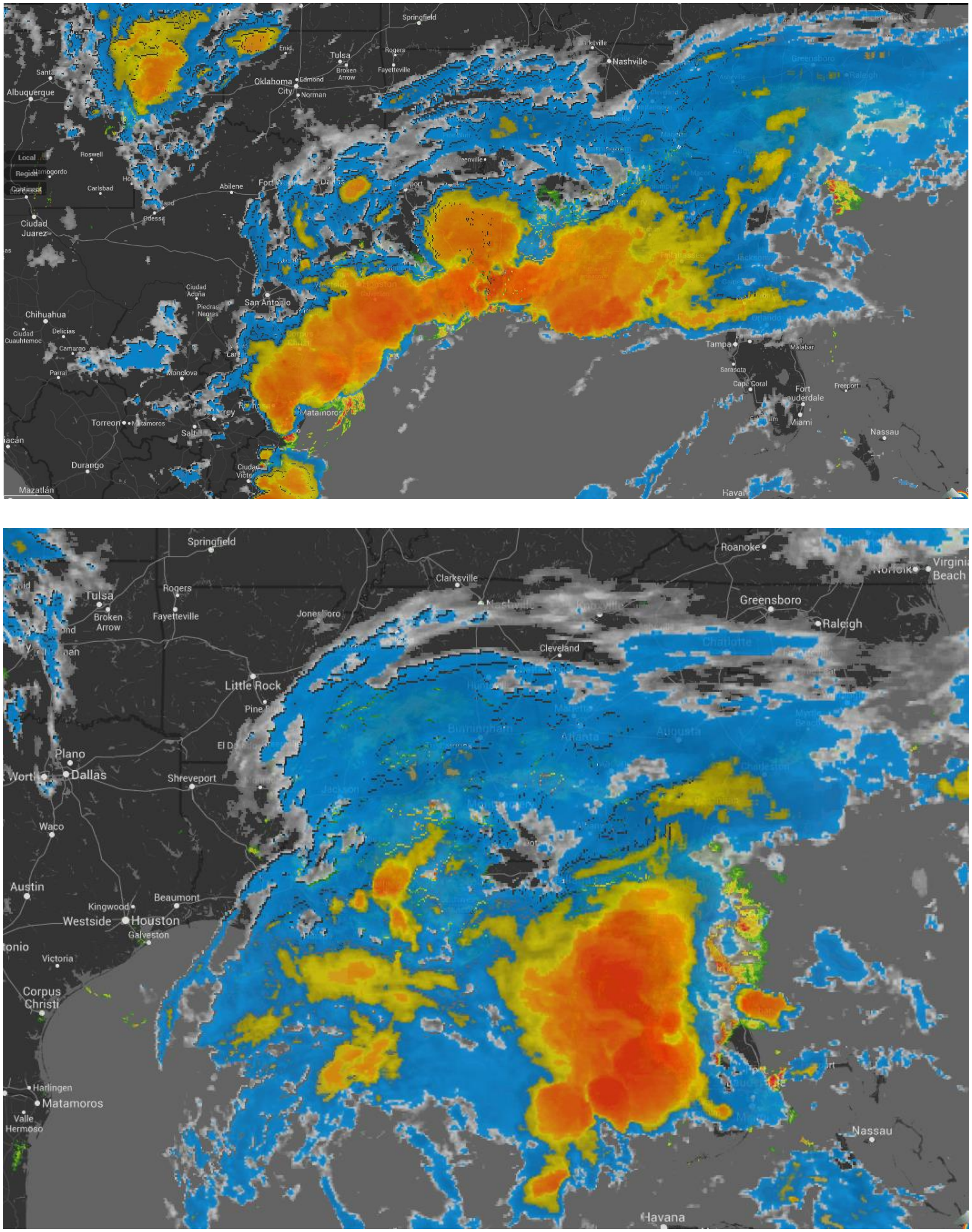

Figure 5.15 Radar imagery of Tropical Storm Barry as it moved through the study area on May 30, 2007, (top) and May 31, 2007, (bottom).

5.14 Thunderstorm of 2008

A series of severe thunderstorms across the region in late May and early June 2008 eroded 27 ha from WSI, 14 ha from ESI, 45 ha from PBI, and 8 ha from Sand Island. Activity during this time may be attributable to Tropical Storm Arthur, which made landfall in Belize on June 1, 2008, though it is unlikely a hurricane striking so far away would have such immediate residual effects on the northern Gulf Coast. The event in question occurred between May 19 and June 4, 2008. Most likely, a storm moving through the area on June 4 led to the appearance of higher loss than actually occurred. However, the observations across all islands indicate that a system of considerable strength would have had to have moved through in order to cause the amount of damage on WSI and PBI. Gulfport, Mississippi, experienced wind gusts upward of 48 km/hr during this time and barometric pressure dropped to 1009 mb. The area received about 80 mm of precipitation during this time, which was unusually high compared to average normal, but low compared to the average hurricane.

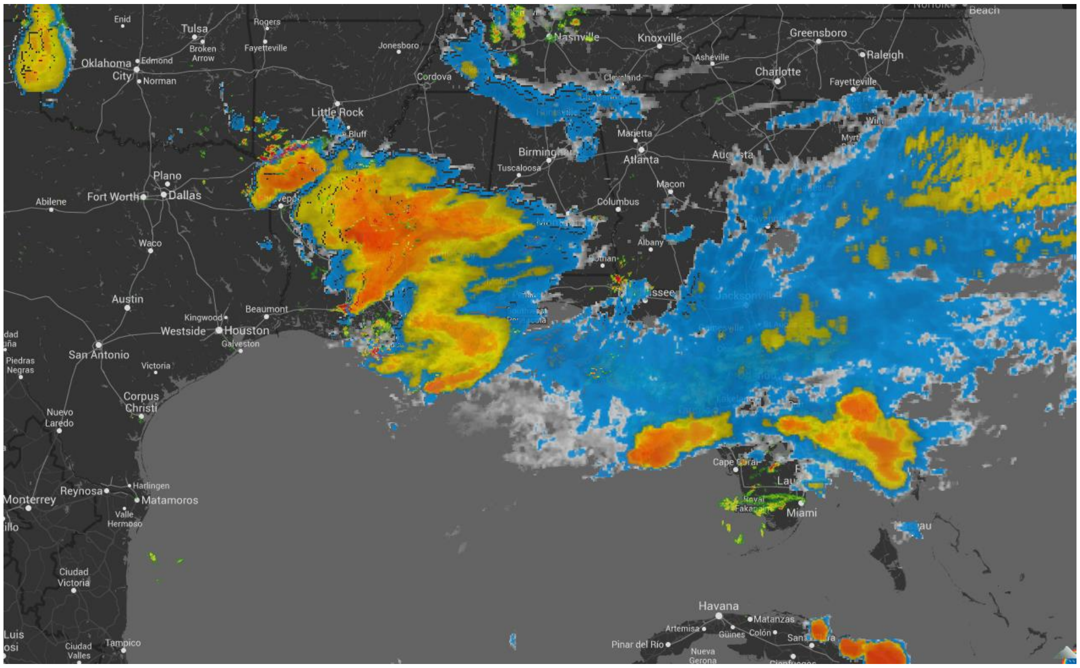

Figure 5.16 Radar imagery taken on May 22, 2008.

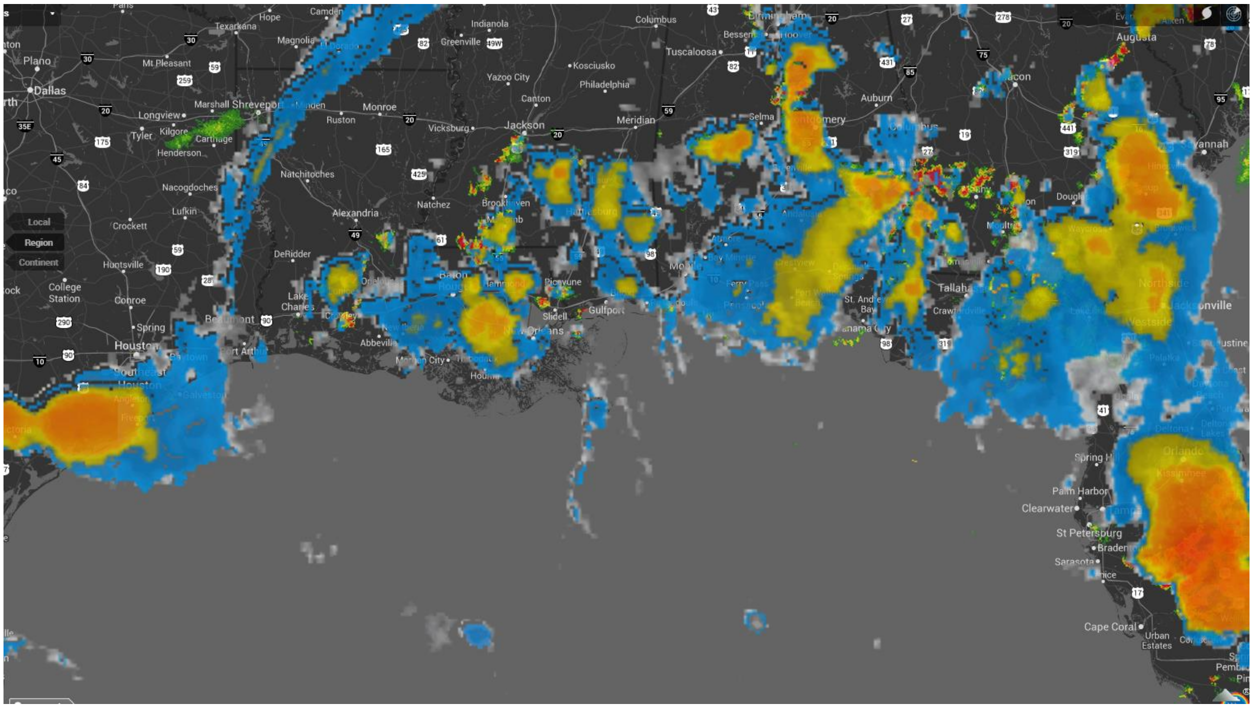

Figure 5.17 Radar imagery of scattered thunderstorms on June 10, 2008.

5.15 Hurricane Gustav

Hurricane Gustav, the first major hurricane to make landfall on the northern Gulf Coast following the end of the 2005 hurricane season, struck on September 1, 2008 near Cocodrie, Louisiana, with a 4.5-m storm surge. Even though Gustav never came within 150 km of the study area (the closest proximity it reached was approximately 168 km west of WSI), it eroded 56 ha from WSI, 31 ha from ESI, 76 ha from PBI, and 10 ha from Sand Island. With each of the islands still in recovery from a catastrophic 2005 hurricane season, Gustav was able to erode enough surface area as a Category 2 to make it the third-worst storm for WSI, fifth-worst storm for PBI, and tied for third-worst storm for Sand Island. While Gustav washed away about half of the surface area of ESI when it hit, the total damage was only 31 ha - about one-third of the area eroded by Katrina, though the island had less area to erode away.

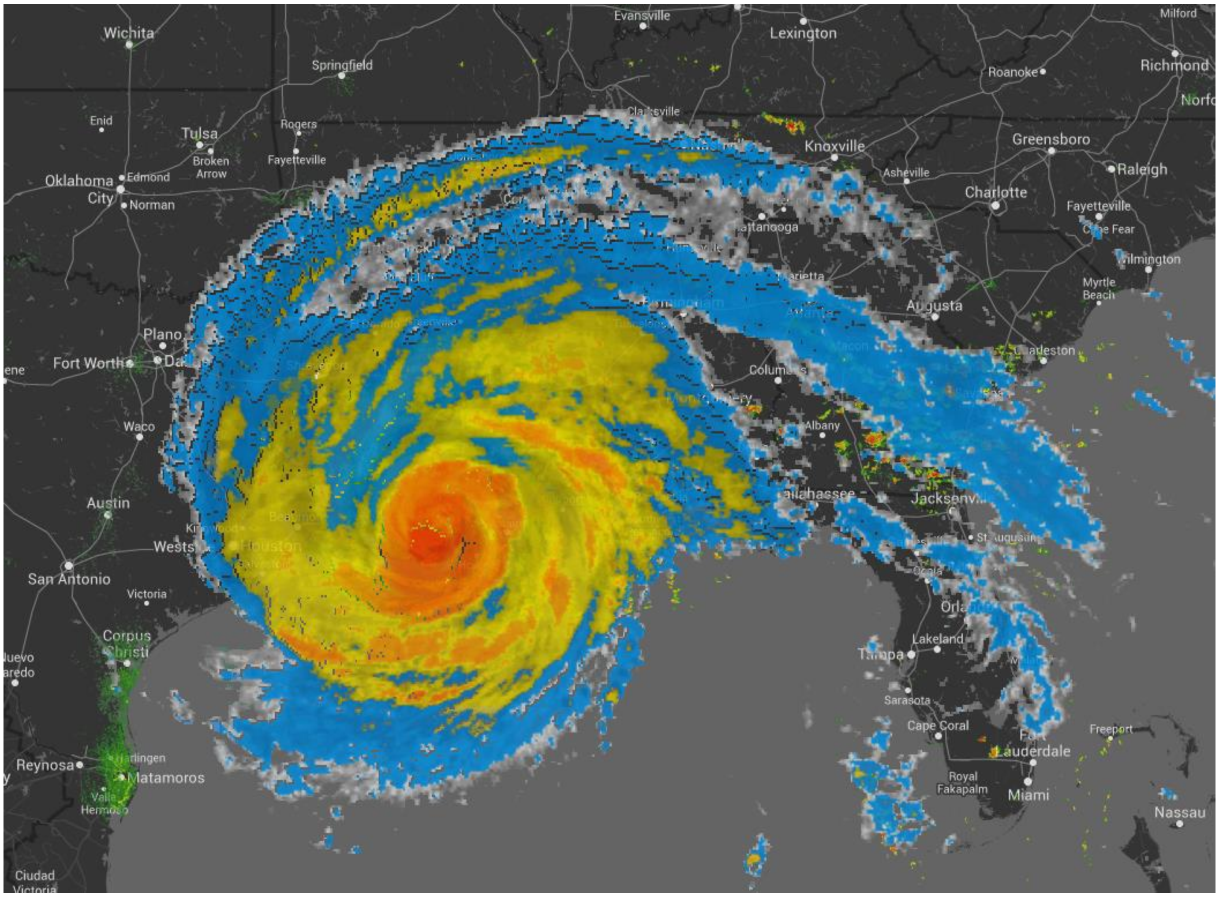

Figure 5.18 Radar image of Hurricane Gustav on August 31, 2008.

5.16 Hurricane Isaac (2012)

Isaac made landfall on August 28, 2012 southwest of the mouth of the Mississippi River with sustained winds of 130 km/hr, or a Category 1 storm. Isaac struck the southeastern tip of Louisiana and moved westward into the state, its closest position 105 km from WSI's westernmost end – about twice as far away as Hurricane Katrina's landfall with one-half of its wind speed. Still, Hurricane Isaac devastated the Mississippi-Alabama barrier island system. Isaac eroded 40 ha from WSI, 55 ha from ESI, 70 ha from PBI, and 7 ha from Sand Island. Isaac managed to erode as much surface from WSI, PBI, and Sand Island as Katrina did, even though its storm surge was 2.4 m - equal to Hurricane Georges' but less than one-third of Katrina's record-breaking surge. However, rainfall in Pascagoula, Mississippi, was 678 mm – about 170 mm more than Katrina. The sheer amount of water falling on the islands could have more to do with its astounding impact than the storm surge or wind speed.

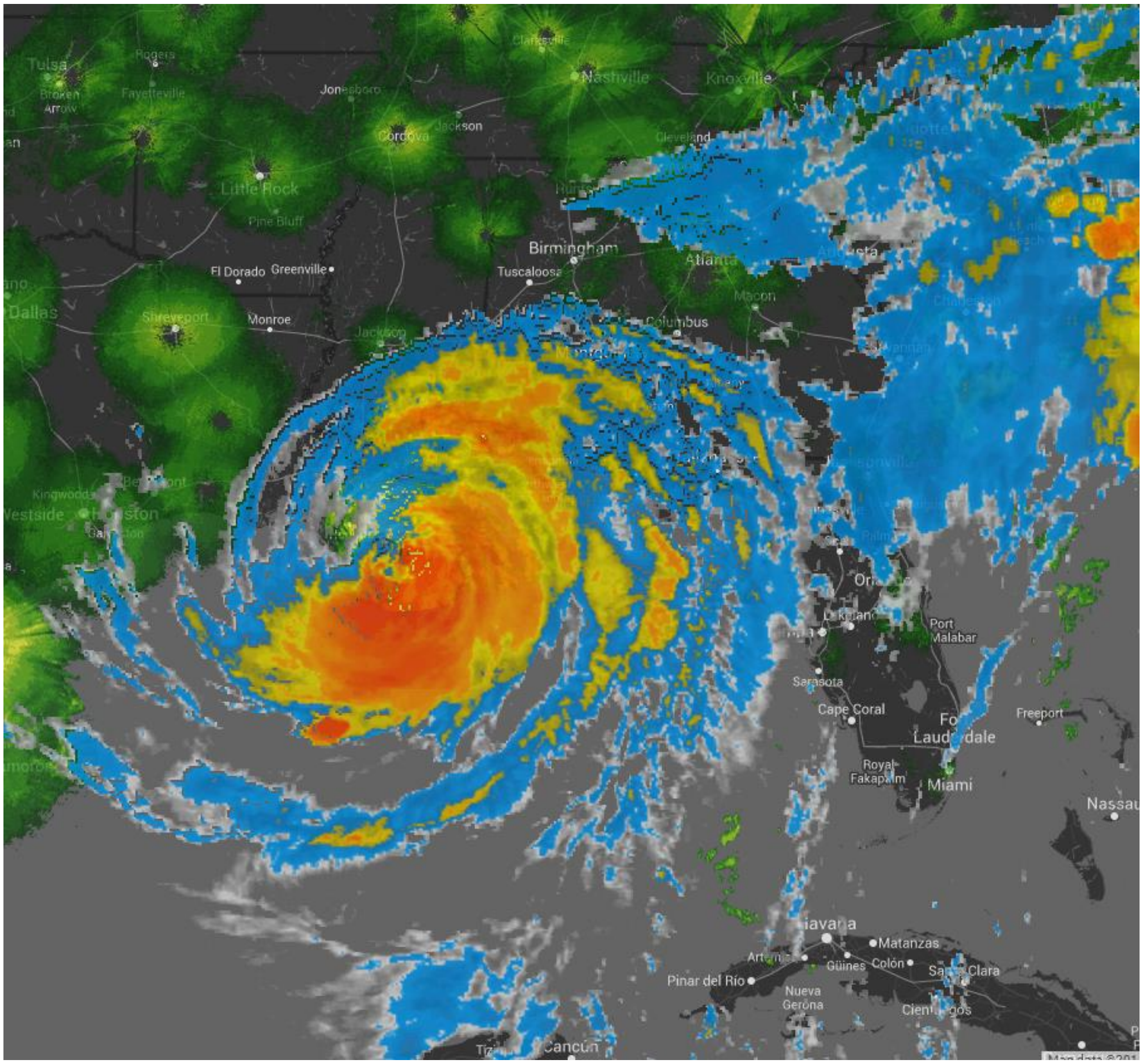

Figure 5.19 A radar image of Hurricane Isaac taken on August 29, 2012.

6. CONCLUSIONS

Catastrophic events caused 54-59% of all land area change on the islands during the 40-year study period. Hurricanes caused 26-37% of all change across the islands, thunderstorms 11-13%, and winter storms 11-14%. Three of the islands lost at least one-quarter of their 1972-1973 areas: WSI 25%, ESI 39% and PBI 38%. Sand Island experienced a 900% gain in surface area. WSI, ESI, and Sand Island are all in post-Katrina (2005) regrowth periods while PBI has destabilized and continues to experience net erosion. The results of this study can serve the Gulf Islands National Seashore in long-term environmental planning. The findings of this study do not significantly depart from previous studies, but rather allocate the changes to specific causes and events and fill in the gaps of time in between as to paint a more detailed picture of the seasonal and annual variability experienced on each of the study areas.

During its infancy, the Mississippi-Alabama barrier island system was defined by sediment influx coming down Appalachia through Mobile Bay during a period of relative sea level rise. Soldiers described an island with snow-white, fine-grained sand that moved in the wind, with little to no vegetation. As time progressed, the island was used as a military base, a port, and more recently, for recreation. The sands were mixed with deep-ocean sediment and dirt, new plant species were brought in and the island grew trees, though only temporarily. Since 1972, the islands have experienced significant area loss, due in part to sea level rise as well as extreme weather events and sediment deprivation. As sea level continues to rise and tropical cyclones become more frequent and severe as a result of climate change, the islands will most likely face continued catastrophic loss.

The islands protect kilometers of coastline and provide resources for commercial and recreational purposes. The current rate of erosion puts the islands under water in less than 40 years with no clear reemergence pattern observed or predicted while channel dredging continues to obstruct westward translocation. Geoengineering alternatives, preservation initiatives, and conservation policies that take into account the natural movement of the system should be examined and implemented before another series of devastating storms causes system-wide destabilization. The only restoration projects on the islands during the study period were nourishment projects, including adding surface area and planting native vegetation. This limits the assessment of how other kinds of preservation and restoration may affect the islands based on the data. Because sediment supply varies from the Gulf and Sound side of the island, jetties and breakwaters would effectively choke off the natural migration and deposition of sediment to the system. Sea walls would be highly impractical given the distance from shore, depth near the island basin, and natural sediment flows. Other methods, such as the construction of oyster habitats, may help alleviate the damage from wave action without disrupting natural sediment flows. It is the recommendation of this study that the National Parks Service continue restoration projects on WSI as planned, focusing on nourishment and restoration, and allow ESI to maintain its natural recovery and erosion. Sediment being lost from PBI is already being contained by Sand Island, and being distributed throughout the system. However, PBI will likely split across the middle, and would likely benefit from strengthening in that area.

The Mississippi-Alabama barrier islands experienced more change in surface area because of catastrophic events than gradual or natural processes from 1972-2014. Hurricanes were the most impactful of all extreme events, although thunderstorms and winter storms combined account for nearly one-quarter of all change. Only storms with a lasting and severe impact were recorded in the surface area record, meaning dozens, possible hundreds, of thunderstorms and mid-latitude cyclones were likely omitted from this research study. It is highly likely that the portion of change caused by extreme events was higher than identified in this study, but almost certainly not lower as gradual exchanges of surface area are easily accounted for even in the absence of imagery.

More work needs to be done in examining the correlation and relationship between various climate factors, such as temperature and precipitation, and surface area change. LIDAR research could shed light on the three-dimensional movement of earth on the islands. How global climate mechanisms like the AMO, PDO, and ENSO contribute to the regional changes observed in climate and extreme weather events should also be explored further. An analysis on stratigraphy and hurricane overwash detection could reveal how trends in increased hurricane activity have impacted the islands before. A current analysis of barrier island sensitivity to sea level variability and extreme climatic events may provide further insight into the mechanics, responses, and sensitivity of islands to climatic change.

By no means do the findings of this study lay to rest the vibrant and ongoing debate around the role of extreme weather events on landscapes. The Mississippi-Alabama barrier island chain is merely one of hundreds of island chains across the planet and have a unique geologic record, even when compared to neighboring island chains like the Chandelieur Islands of Louisiana. The depth of this research study showed how extreme events have become the dominant force in changing surface area on the islands, and how those events have become more destructive in the last two decades. This study also showed how sea level serves as the primary driver of seasonal variation on the islands, likely driving much of the long-term erosion observed on the islands. Even if hurricanes stopped altogether, the islands would likely continue to experience net erosion due to sea level rise. But hurricanes are not going to stop and are likely to become more severe, both in frequency and intensity. Though the future of the islands remains unknown, the data and results of this study suggest that the islands found by the earliest American settlers may cease to exist by the end of this century. However, efforts to preserve the islands show promise in stalling erosion. Thus, at the conclusion of this paper, which started in prose and therefore must end in such, one profound truth comes to mind:

> The future is ever a misted landscape, no man foreknows it, but at cyclical turns. There is a change felt in the rhythm of events. Robinson Jeffers (1950)

REFERENCES

Archer, David. "Global Warming : Understanding the Forecast / David Archer." n.p.: Malden, MA : Blackwell Pub., c2007., 2007. Agricola.

Baker, V. R. 1998. Catastrophism and Uniformitarianism; Logical Roots and Current Relevance in Geology. Geological Society Special Publications, 143, 171-182.

Balsillie, James H., and Joseph F. Donoghue. "High Resolution Sea-Level History for the Gulf of Mexico Since the Last Glacial Maximum." Report of Investigation - Florida Geological Survey (2004)

Bazerman, C., 1993. Intertextual Self-Fashioning: Gould and Lewontin's Representations of Literature. In: Selzer, J. Ed. Understanding Scientific Prose. Madison: U of Wisconsin P, 20-41.

Bearss, Edwin C. 1984. “Gulf Islands – Ship Island, Historic Resource Study.” Gulf Island National Seashore. National Park Services.

Bentley, Samuel J., Yoko Furukawa, and W. Chad Vaughan. "Record of Event Sedimentation in Mississippi Sound." Transactions - Gulf Coast Association of Geological Societies 50.(2000): 715-723.

Bentley, Samuel J., et al. "Preservation Potential of Event Layers; Observations of Hurricane Sedimentation in the Northern Gulf of Mexico." Abstracts with Programs - Geological Society of America 32.7 (2000): 513.

Bird, M. I., W. E. N. Austin, C. M. Wurster, L. K. Fifield, M. Mojtahid & C. Sargeant (2010) Punctuated Eustatic Sea-level Rise in the Early Mid-Holocene. Geology [Boulder], 38, 803-806.

Blum, M. D., Et Al. 2003. Middle Holocene Sea-Level and Evolution of the Gulf of Mexico Coast. Transactions - Gulf Coast Association of Geological Societies, 53, 64-77.

Bonisteel-Cormier, J. M., et al. 2011. The Application of Lidar in Monitoring Barrier Island Volumetric Change and Shoreline Position at the Gulf Islands National Seashore, Mississippi. Abstracts with Programs - Geological Society of America, 43(3), 15-15.

Brooks, H. E. "Severe Thunderstorms and Climate Change." Atmospheric Research 123.(n.d.): 129-138. Science Citation Index.

Butler, Benjamin F. 1892. Butler’s Book: Autobiography and Personal Reminiscences of Major-General Benj. F. Butler. Boston, Mass.

Byrnes, M. R., R. A. McBride, S. Penland, M. W. Hiland, and K. Westphal, 1991, Historical Changes in Shoreline Position along the Mississippi Sound Barrier Islands: GCSSEPM Foundation Twelfth Annual Research Confrence, p. 43-55.

Byrnes, M. R., et al. 2013. Historical Sediment Transport Pathways and Quantities for Determining an Operational Sediment Budget: Mississippi Sound Barrier Islands. Journal of Coastal Research, 166-183.

Carter, G. A., et al. 2011. Historical Changes in Seagrass Coverage on the Mississippi Barrier Islands, Northern Gulf of Mexico, Determined from Vertical Aerial Imagery (1940–2007). Geocarto International, 26(8), 663-673.

Changnon, SA. "Thunderstorm Rainfall in the Conterminous United States." Bulletin of the American Meteorological Society 82.9 (n.d.): 1925-1940. Science Citation Index.

Christopherson, Robert W. 2009 Geosystems. HathiTrust.

Cipriani, L. E. and Stone, G. W. 2001. Net Longshore Sediment Transport and Textural Changes in Beach Sediments Along the Southwest Alabama and Mississippi Barrier Islands, U.S.A. Journal of Coastal Research, 17(2), 443-458.

Cipriani, Luigi E., and Gregory W. Stone. "Net Longshore Sediment Transport and Textural Changes in Beach Sediments along the Southwest Alabama and Mississippi Barrier Islands, U.S.A." Journal of Coastal Research 17.2 (2001): 443-458.

Clark, P. U. and Mix, A. C. 2002. Ice Sheets and Sea Level of The Last Glacial Maximum. *Quaternary Science Reviews*, 21(1–3), 1-7.

Curray, J. R., 1959. *Sediments and History of The Holocene Transgression Continental Shelf, Northwest Gulf of Mexico.*

Delcourt, P. A., *Et Al.* 1980. Quaternary Vegetation History of The Mississippi Embayment. *Quaternary Research*, 13(1), 111-132.

Curray, J. R., 1959. Sediments and History of the Holocene Transgression Continental Shelf, Northwest Gulf of Mexico.

Del Genio, A.D., M.-S. Yao, and J. Jonas, 2007: Will moist convection be stronger in a warmer climate? Geophys. Res. Lett., 34, L16703, doi:10.1029/2007GL030525.

DeForest, John William. A Volunteers Adventure: A Union Captain's Record of the Civil War. New Haven, Ct., 1946.

Emanuel, K.A., "Increasing Destructiveness of Tropical Cyclones over the Past 30 Years (Adobe Pdf), Nature, 436, 686-688, 4 August 2005.

Emanuel, K., and A. Sobel, 2013: Response of tropical sea surface temperature, precipitation, and tropical cyclone-related variables to changes in global and local forcing. J. Adv.

Model. Earth Sys., 5, doi:10.1002/jame.20032. Copyright 2013, American Geophysical Union

Fairbridge, R. W., 1961. Eustatic Changes in Sea Level. United States, 99-185.

Flocks, J. G. and Dewitt, N. T. 2009. Geologic Control on Barrier Island Stability; Ship and Horn Islands, Mississippi. Abstracts With Programs - Geological Society of America, 41(1), 13-14.Flower, B. P., *Et Al.* 2004. Late Pleistocene and Holocene Glacial Meltwater Input To The Gulf of Mexico. *Abstracts With Programs - Geological Society of America,* 36(5), 193-193.

Fritz, H. M., et al., 2007. H.M. Fritz, G. Bloom, R. Sokoloski, J. Singleton, A. Fuggle, B.G. McAdoo, A. Moore, C. Grass, B. Tate. Hurricane Katrina Storm Surge Distribution and Field Observations on the Mississippi Barrier Islands. Estuarine, Coastal and Shelf Science, 17 (2007), pp. 12–20

Gerdes, R. G., Et Al. 1980. Effects of Hurricane Frederic on Dauphin Island, Alabama. Shore & Beach, 48(3), 20.

Golden, Joseph H. Life Cycle of Florida Keys' Waterspouts / Joseph H. Golden ; National Severe Storms Laboratory. n.p.: Norman, Okla. : U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, Environmental Research Laboratories, National Severe Storms Laboratory, 1974., 1974. Louisiana State University.

Gould, S. (1990). Wonderful life : the Burgess Shale and the nature of history / Stephen Jay Gould. New York : W.W. Norton, c1989.

Gould, S. J., 2007. *Punctuated Equilibrium / Stephen Jay Gould.* Cambridge, Mass. : Belknap Press of Harvard University Press, 2007.

Grinsted, Aslak, John C. Moore, and Svetlana Jevrejeva. 2009. "Homogeneous Record of Atlantic Hurricane Surge Threat Since 1923." Proceedings of the National Academy of Sciences of the United States of America 109.48 (n.d.): 19601-19605. Biological Abstracts 1969 - Present.

Gulf Islands National Seashore. 2013. National Park Service. http://www.nps.gov/guis/index.htm Accessed 05 May 2013.

Hayes, M. O., 2005. Barrier Islands Encyclopedia of Earth Science Series. Netherlands: Springer : Dordrecht, Netherlands, 117-119.

Hecht, J. 2009. Beware Earth-Shattering Headlines. *New Scientist,* 201(2694), 24.

Hermann, M. F., B. Chris, S. Robert, S. Justin, F. Andrew, G. M. Brian, M. Andrew, G. Chad & T. Banks (2007) Hurricane Katrina storm surge distribution and field observations on the Mississippi Barrier Islands. Estuarine, Coastal and Shelf Science, 74, 12-20.

Hollandsworth, James G. 2014. Union Soldiers on Ship Island Suring the Civil War. Mississippi History Now. http://mshistorynow.mdah.state.ms.us/articles/211/union-soldiers-on-ship-island-during-the-civil-war

Iberville, Pierre. 2010. Iberville's Gulf Journals. The University of Alabama Press. Translated By Richebourg Mcwilliams

Intergovernmental Panel on Climate Change (2007), Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.).Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

International Panel on Climate Change. 2013. Fifth Assessment Report. http://www.ipcc.ch/

Keim, Barry D., Robert A. Muller, and Gregory W. Stone. "Spatiotemporal Patterns and Return Periods of Tropical Storm and Hurricane Strikes from Texas to Maine." Journal of Climate 20.14 (2007): 3498-3509. Academic Search Complete. Web. 12 Feb. 2014.

Keqi, Z. and Leatherman, S. 2011. Barrier Island Population Along the U.S. Atlantic and Gulf Coasts. *Journal of Coastal Research,* 27(2), 356-363.

Knowles, Stephen C., and Julie Dean Rosati. Geomorphic and Coastal Process Analysis For Ship Channel Planning At Ship Island, Mississippi / By Stephen C. Knowles, Julie D. Rosati, Coastal Engineering Research Center ; Prepared For US Army Engineer District. n.p.: [Vicksburg, Miss. : U.S. Army Engineer Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1989], 1989. Louisiana State University.

Kunkel, K. E., D. R. Easterling, D. A. R. Kristovich, B. Gleason, L. Stoecker, and R. Smith, 2012: Meteorological causes of the secular variations in observed extreme precipitation events for the conterminous United States. J. Hydrometeor., 13, 1131–1141.

Leatherman, S. P. "Migration of Assateague Island, Maryland, by Inlet and Overwash Processes." Geology [Boulder] 7.2 (1979): 104-107.

Leatherman, Stephen P. Barrier Island Migration with Holocene Sea Level Rise. Proceedings of the Symposium on Coastal Sedimentology 6.(1983): 127-140.

Levermann, A., *et al.* 2013. The Multimillennial Sea-Level Commitment of Global Warming. *Proceedings of the National Academy of Sciences of the United States of America,* 110(34), 13745-13750.

Marriner, N., Morhange, C. and Skrimshire, S. 2010. Geoscience Meets the Four Horsemen? Tracking the Rise of Neo-Catastrophism. *Global and Planetary Change,* 74(1), 43-48.

Marsh, Bob. 2013. Mississippi Barrier Islands: A Guide for Kayakers, Campers and Naturalists. Accessed January 15, 2013. Http://Www.Barrierislandsms.Com/Guide.Htm#Ship_Island

McBride, R. A., M. R. Byrnes, and M. W. Hiland, 1995, Geomorphic response-type model for barrier coastlines: a regional perspective: Marine Geology, v. 126, p. 143-159.

McQuaid, John (2012) "Hurricanes and climate change." NOVA http://www.pbs.org/wgbh/nova/earth/hurricanes-climate.html

Morton, R. A. 2008. Historical Changes in the Mississippi-Alabama Barrier-Island Chain and the Roles of Extreme Storms, Sea Level, and Human Activities. *Journal of Coastal Research,* 24(6), 1587-1600.

Morton, R. A. 2010. First-Order Controls of Extreme-Storm Impacts on the Mississippi-Alabama Barrier-Island Chain. *Journal of Coastal Research,* 26(4), 635-648.

National Aeronautics and Space Administration (NASA) (2013) Physical Oceanography DAAC. AVHRR Oceans Pathfinder Global Equal-angle Best SST (NOAA/NASA). NASA JPL Physical Oceanography DAAC, Pasadena, CA.

National Climate Assessment. 2009. Global Climate Change Impacts in the United States. http://nca2009.globalchange.gov/.

National Climatic Data Center. 1993 Group. Research Customer Service, and Neal. Lott. "Big One! Microform / Big One! A Review of The March 12-14, 1993, "Storm of The Century" / A Review of The March 12-14, 1993, "Storm of The Century." Agris. Web. 12 Feb. 2014.

National Climate Data Center. 2013. http://www.ncdc.noaa.gov/.

National Oceanic and Atmospheric Administration (2013) Earth System Research Laboratory | Physical Sciences Division http://www.esrl.noaa.gov/psd/data/gridded/tables/ocean.html

Nummedal, Dag, et al. "Geologic Response To Hurricane Impact On Low-Profile Gulf Coast Barriers." Transactions - Gulf Coast Association of Geological Societies 30.(1980): 183-194.

Osborn TJ and Jones PD (2014) The CRUTEM4 land-surface air temperature data set: construction, previous versions and dissemination via Google Earth. Earth System Science Data 6, 61-68 (doi:10.5194/essd-6-61-2014). [See also: Earth System Science Data Discussions (2013) 6, 597-619 (doi:10.5194/essdd-6-597-2013).]

Nummedal, Dag, *et al*. "Geologic Response to Hurricane Impact on Low-Profile Gulf Coast Barriers." Transactions - Gulf Coast Association of Geological Societies 30.(1980): 183-194.

Otvos, E. G., Jr. 1970. Development and Migration of Barrier Islands, Northern Gulf of Mexico. *Geological Society of America Bulletin,* 81(1), 241-246.

Otvos, E. G., Jr., 1979. Barrier Island Evolution and History of Migration, North Central Gulf Coast. United States: Acad. Press : New York, N.Y., United States, 291-319.

Otvos, E. G. 2005. Coastal Barriers, Gulf of Mexico: Holocene Evolution and Chronology. *Journal of Coastal Research,* 141.

Otvos, Ervin G. "Beach Ridges Encyclopedia of Earth Science Series." 172-177. Netherlands: Springer : Dordrecht, Netherlands, 2005.

Otvos, E. G. and Carter, G. A. 2008. Hurricane Degradation - Barrier Development Cycles, Northeastern Gulf of Mexico: Landform Evolution and Island Chain History. *Journal of Coastal Research,* 24(2), 445-478.

Otvos, E. G. and Carter, G. A. 2013. Regressive and Transgressive Barrier Islands on the North-Central Gulf Coast — Contrasts In Evolution, Sediment Delivery, and Island Vulnerability. *Geomorphology,* 198, 1-19.

Otvos, Ervin G., and Marco J. Giardino. "Interlinked Barrier Chain and Delta Lobe Development, Northern Gulf of Mexico." Sedimentary Geology 169.1-2 (2004): 47-73.

Penland, S., P.F. Connor, Jr., A. Beall, S. Fearnley, and S.J. Williams. 2005. Changes in Louisiana's Shoreline: 1855-2002. Journal of Coastal Research SI 44:7-39.

Pidwirny, M. (2006). "Climate Classification and Climatic Regions of the World". Fundamentals of Physical Geography, 2nd Edition. Date Viewed. http://www.physicalgeography.net/fundamentals/7v.html

Pidwirny, M. (2006). "The Mid-Latitude Cyclone". Fundamentals of Physical Geography, 2nd Edition. Date Viewed. http://www.physicalgeography.net/fundamentals/7s.html

Pirazzoli, P. A. and Pluet, J., 1991. *World Atlas of Holocene Sea-Level Changes / Paolo Antonio Pirazzoli ; Assistant, Jean Pluet.* Amsterdam ; New York : Elsevier, 1991.

Pushcharovskiy, Y. M. 1986. Academician Nikolay Sergeyevich Shatskiy (On The 90th Anniversary of His Birth) [August 28, 1895-August 1, 1960]. *Geotectonics,* 19(4), 259-268.

Robinson Jeffers (1950), U.S. poet. Prescription of Painful Ends (l. 3-4). . . Oxford Book of American Verse, The. F. O. Matthiessen, ed. (1950) Oxford University Press.

Rosati et al., 2007. J.D. Rosati, M.R. Byrnes, M.B. Gravens, S.F. Griffee. Mississippi Coastal Improvement Project Study. Regional Sediment Budget for the Mississippi Mainland and

Barrier Island Coasts, U.S. Corps of Engineers, Engineer Research and Development Center, Coastal Hydraulics Laboratory, Publication No. 10-1 (2007) (183 pp.).

Rosati, J. D. and Stone, G. W. 2009. Geomorphologic Evolution of Barrier Islands along the Northern U S. Gulf of Mexico and Implications for Engineering Design in Barrier Restoration. Journal of Coastal Research 25

Rucker, J. B., and J. O. Snowden, 1990, Barrier Island Evolution and Reworking by Inlet Migration along the Mississippi-Alabama Gulf Coast: Gulf Coast Association of Geological Societies, p. 745-753.

Saucier, R. T., 1994. *Geomorphology and Quaternary Geologic History of the Lower Mississippi Valley / Prepared By Roger T. Saucier ; Prepared For the President, Mississippi River Commission.* [Vicksburg, Miss. : U.S. Army Engineer Waterways Experiment Station, 1994.

Schmid, K., 2000, Historical Evolution of Mississippi's Barrier Islands: Mississippi Environment, v. January/February, 2000.

Schwartz, Maurice L. 1973. The Multiple Causality of Barrier Islands. 393-396. United States: Dowden, Hutchinson & Ross : Stroudsburg, PA, United States, 1973

Scott, H. 2007. Stephen Jay Gould and the Rhetoric of Evolutionary Theory. *Rhetoric Review*, 26(2), 120-141.

Shepard, F. P., 1963. Thirty-Five Thousand Years of Sea Level. United States, 1-10.

Sherman-Morris, Kathleen, Michael E. Brown, and Charles Larry Wax. Mississippi Weather and Climate. Jackson: University Press of Mississippi, 2012. Ebook Collection (Ebscohost). Web. 12 Feb. 2014.

Sherman, Andrew M. In the Lowlands of Louisiana in 1863: An Address Delivered By Rev. Andrew M. Sherman At the Forty-Second Reunion of the Twenty-Third Conn. Regimental Association. Morristown, N. J., 1908.

Shu, Yu, Yi-Nong Pan, and Wei Wang. "Statistic Characteristics of MCSs over Asia and Western Pacific Region." Journal of Tropical Meteorology 18.4 (2012): 457-472. Academic Search Complete. Web. 12 Feb. 2014.’

Smith, George G. Leaves from a Soldier’s Diary: The Personal Record of Lieutenant George G. Smith, Co. C, 1st Louisiana Regiment Infantry Volunteers [White] During the War of Rebellion. Putnam, Ct., 1906.

Smith, Q. H. T., Heap, A. D. and Nichol, S. L. 2010. Origin and Formation of an Estuarine Barrier Island, Tapora Island, New Zealand. *Journal of Coastal Research*, 26(2), 292-300.

Stapor, F. W., Jr. and Stone, G. W. 2004. A New Depositional Model for the Buried 4000 Yr BP New Orleans Barrier; Implications for Sea-Level Fluctuations and Onshore Transport From A Nearshore Shelf Source. *Marine Geology,* 204(1-2), 215-234.

Stone, Gregory W., *et al*. "The Importance of Extratropical and Tropical Cyclones on the Short-Term Evolution of Barrier Islands along the Northern Gulf of Mexico, USA." Marine Geology 210.1-4 (2004): 63-78.

Stone *et al*., 2004. G.W. Stone, D.A. Pepper, J. Xu, X. Zhang. Ship Shoal. 2004. A prospective borrow site for barrier island restoration. Journal of Coastal Research, 20, pp. 70–88

Stone, G. W., D. M. Fitzgerald & I. Georgihou. 2004. Louisiana Coastal Area (LCA), Gulf Shoreline Restoration Study. Appendix D to Louisiana Coast-wide Ecosystem Study. ed. U. S. A. C. o. Engineers. Louisiana Gulf Shoreline Reconstruction.

Trapp, R. et al (2007) Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. Proceedings of the National Academy of Sciences, 104 (50), 19719-19723.

Twichell, D., 2011. The Shallow Stratigraphy and Sand Resources Offshore of the Mississippi Barrier Islands [Electronic Resource] Reston, Va. : U.S. Dept. of the Interior, U.S. Geological Survey, 2011.

Union of Concerned Scientists (UCS). 2013. http://www.ucsusa.org/

USGS, 2009. Hurricane Impact and Recovery Shoreline Change Analysis and Historical Island Configuration: 1700s to 2005. Chapter A of of Sand Resources, Regional Geology and Coastal Processes of the Chandeleur Islands Coastal System: An Evaluation of the Breton National Wildlifre Reguge. Http://Pubs.USGS.gov/Sir/2009/5252/Downloads/Chapter-A/Chapter-A.Pdf

Waller and Malbrough, 1976. T.H. Waller, L.P. Malbrough. Temporal Changes in the Offshore Islands of Mississippi. Water Resources Institute, Mississppi State University (1976) (109 pp.)

Webster, P.J., G.J. Holland, J.A. Curry, and H.-R. Chang, "Changes in Tropical Cyclone Number, Duration, and Intensity in A Warming Environment", Science, 309, 1844-1846, 16 September 2005.

Williams, Jolene. “Re: NPS Research Permit and Reporting System Upgrade Effective July 3, 2013.” Message to the Author. 16 September 2013. Email.

Wormeley, Kathrine P. The United States Sanitary Commission: A Sketch of Its Purposes and Its Works. Boston, Mass., 1863.

Zhang, Keqi, Bruce C. Douglas, and Stephen P. Leatherman. "Global Warming and Coastal Erosion." Climatic Change 64.1-2 (2004): 41-58. GeoRef. Web. 12 Feb. 2014.

VITA

Rebekah Jones was born in Windber, Pennsylvania in 1989. Rebekah enrolled at Syracuse University and earned a Bachelor of Arts with dual majors in geography and journalism in August 2012. While enrolled at SU, Rebekah worked at the Syracuse Center of Excellence in Energy and Environmental Systems as a communications and special projects intern. She also worked at various newspapers, including *The NewsHouse of Syracuse University*, *The Daily Orange*, *The Post-Standard*, *The New Times*, *DemocracyWise* and others as a reporter and editor. She entered the graduate program at Louisiana State University in August of 2012. Rebekah worked with the Southern Climate Impacts Planning Program and Southern Regional Climate Center during her time at LSU.