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Dendrotempestology: Identifying the Statistical Relationship Between Hurricanes and Tree Growth in the Pine Savannas of Coastal Mississippi

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DENDTROTEMPESTOLOGY: IDENTIFYING THE STATISTICAL RELATIONSHIP BETWEEN HURRICANES AND TREE GROWTH IN THE PINE SAVANNAS OF COASTAL MISSISSIPPI

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
Clay Stephens Tucker
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I would be remiss if I didn’t thank the numerous faculty across LSU that have only increased my love for Louisiana, the Gulf Coast, and its geography. Drs. Patrick Hesp, Richard

Kesel, Sam Bentley, and Kory Konsoer were very influential in guiding my interests in geomorphology and Earth's surface processes. My knowledge of South Louisiana gained from Drs. Bob Rohli and Craig Colten has strengthened my love of Louisiana's place in history. I have accompanied all of these professors in the field and it was a complete joy to see their research and knowledge at work. I can only hope to pass this knowledge to others in the future.

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ABSTRACT

Coastal trees in the Gulf of Mexico region are impacted by high winds, heavy precipitation, and storm surge from hurricanes. This study attempts to establish the relationship between pine trees in Grand Bay National Estuarine Research Reserve (GBNERR), Mississippi, U.S.A. and hurricanes that impacted that area in the last 80 years. Indexed ring widths are analyzed against hurricane high winds and storm surge records. In this study, I find tree growth is significantly ($p \leq 0.05$) reduced the year after a hurricane. Suppression chronology analysis assesses the relationship of delayed or lagged effects of hurricanes on tree growth and finds tree growth is stunted for three years following the top ten ranked storms impacting this site. Additionally, earlywood tree growth, which forms in spring months, is also significantly related to the Palmer Drought Severity Index. This study shows that trees are resilient to hurricanes, and I hypothesize that they survive by concentrating growth on crown repair thus reducing growth in the stem, or trunk of the tree. This research can be used to expand knowledge on coastal restoration efforts, the effects of climate change on maritime forests, and is a step forward in producing longer chronologies of hurricane occurrences.

1. INTRODUCTION

On August 29, 2005, Hurricane Katrina made landfall near Bay St. Louis, Mississippi. The storm produced wind speeds in excess of 53 ms^{-1} and a storm surge of 8.2 m in Gulfport, MS (Burton and Hicks 2005; Knabb et al. 2005).The property damage from Hurricane Katrina totaled $108 billion, at least 1,833 people died, and the events proceeding the hurricane displaced more than half of the residents of New Orleans, Louisiana (Knabb et al. 2005). This represents the deadliest hurricane since the 1928 Okeechobee Hurricane and the costliest natural disaster in United States hurricane history. Planning for and prediction of future hurricanes is essential for the protection of lives and property (Knabb et al. 2005). The Gulf of Mexico coast provides a suitable area for improving knowledge of the economic importance of coastal wetlands (Barbier et al. 2013).

Predictions of future events have been based on return periods, or the likelihood of an event occurring. Return periods are empirically based on the occurrences found in historical data. Keim et al. (2007) presents a good example of return periods of hurricane occurrences in the North Atlantic. Return periods for that study were calculated by dividing the number of hurricanes by the number of years of the hurricane record. For example, St. Petersburg, Florida received two major hurricanes within the 105-year record and is expected to experience wind speeds of greater than or equal to 50 ms^{-1} once every 52 years. Though this is a useful statistic, the available data record used for analysis includes only 105 years of data (1901 – 2005). To strengthen the confidence of this return period estimate, more robust statistics can be applied or the period of record can be lengthened.

Extreme value statistics are a robust form of analysis used to produce return periods that estimate the frequency of hurricanes and their associated climatic variables beyond the known period of record (Elsner et al. 2012; Trepanier et al. 2015). Proxy records are used to reconstruct past climate to increase the amount of climate data known beyond human-written records. Dendroclimatology uses tree rings as a proxy for past climate. Trees are susceptible to precipitation and temperature changes and other environmental forcings, and they record this information in annual growth bands (Douglass 1909, 1944). Dendrochronology relies on seven principles. One of these principles is the Principle of Limiting Factors (Speer 2010). A limiting factor, also known as a stressor, is an environmental component that limits primary or secondary growth of a tree from year-to-year. The largest limiting factor of growth for trees is water (Loomans 1993). If a tree receives adequate amounts of water, it grows well. Other stressors include lack of sunlight, temperature, insect infestation, and competition from other plants, to name a few (Douglass 1909; Fritts 1976). Particularly for this study, a stressor of trees along the Gulf of Mexico Coast is saltwater and its effects (e.g. increased evaporation, decreased soil moisture, and mineral accumulation in the plant) (Conner et al. 1997; Pezeshki et al. 1990). This study explores the effects of hurricanes on trees and if tree rings can be used as proxies for past hurricanes.

In the following section of this thesis, past studies in hurricane climatology using different proxies are reviewed. Next, field methods specific to this study are explained, including use of coastal pine trees for dendrochronological research, and statistical methods specific to this study. Different statistical methods are compared and contrasted. Lastly, relationships between tree growth and hurricane characteristics are discussed, along with possible explanations for this relationship.

1.1 Literature Review

Dendroclimatology is the study of past climate using trees, usually using growth patterns assessed through annual growth rings. Trees form growth bands each year that are affected by many variables such as water and nutrient availability (Douglass 1909; Fritts 1976). This allows dendroclimatology to be effective in determining annual, and often seasonal, climate forcings (e.g., Briffa 2000; Fritts 1976; Speer 2010). Evidence of precipitation variability (e.g., Therrell et al. 2006), global teleconnections (e.g., Therrell 2011), wildfire occurrences (e.g., Harley et al. 2012a), flooding regimes (e.g., Smith et al. 2013; Stahle et al. 2003), and hurricane occurrences (e.g., Miller et al. 2006) have been found through the use of dendroclimatology.

Tree rings have been used widely for reproducing both climatic and terrestrial forcing for tree growth and response (Briffa 1995; Fritts 1976; Therrell 2011). Growth bands provide a rich source of high-resolution paleoclimatic data (Briffa 2000; Speer 2010). Trees can supply seasonal data because they form two separate growth bands during a year. During the beginning of the typical growing season (March – May, for southeast U. S. pine species), the growth band portion known as the "earlywood" grows less densly than the growth bands that form during the late growing season (June – October), also known as "latewood" (Byram and Doolittle 1950; Jackson 1952; Langdon 1963).

The driving force for this research is to study the effects of hurricanes on the Gulf of Mexico coastal landscape. This study will assess these effects in two ways: (1) by increasing knowledge on hurricane occurrences in the known record thus improving hurricane frequency analyses, and (2) by increasing the amount of knowledge of hurricane impacts on coastal forest ecology. By increasing our knowledge of damage done by hurricanes, we can better protect humans and their property for future hurricane occurrences.

Paleotempestology, a term coined by Dr. Kam-biu Liu at Louisiana State University (LSU), is the study of past hurricane occurrences (Murnane and Liu 2004). Some hurricane occurrences are recorded as far back as 1,000 years ago, however, those records are from China and contain few quantitative records of the storms (Louie and Liu 2004). Some hurricanes are recorded by ships during the Colonial Era as far back as the 1500s, but the written record for landfalling hurricanes in the Atlantic Basin extends back until the 1700s when newspapers became popular in the United States (Boose 2004; Mock 2004). Several proxy methods are now used to reconstruct hurricanes before that record. These studies include, but are not limited to, corals (Kilbourne et al. 2011) , sediments (Hesp and Short 1999; Liu and Fearn 1993, 2000), speleothems (Frappier et al. 2007; Knabb et al. 2005), and, most recently, trees (Miller et al. 2006).

Hurricane effects on coastal ecology are debated. First, the sedimentation processes cause by hurricane storm surge are not yet well understood (Tornqvist et al. 2007; Turner et al. 2006). This sedimentation directly affects the nutrients available to the ecosystem and the substrate on which plants can grow. Numerous studies examine the direct effects of hurricanes on the total coastal pine savanna ecosystem (Batista and Platt 2003; Curtis 1942; Doyle et al. 1995; Platt et al. 2002). Some of these studies note that a hurricane occurrence is not completely detrimental to coastal forests. They are noted as a “disturbance” and not a total “catastrophe”, wherein a disturbance happens more frequently, does not completely reset the ecosystem, and rather acts to weed out weaker specimens allowing the strong to thrive. In other words, these coastal pine trees are well adapted to coastal ecosystems and instead of large amounts of tree mortality, the trees are defoliated and roots are starved of oxygen. The tree must then concentrate on repairing itself rather than expanding its stem. Trees not stressed by coastal processes may not respond the same to these hurricanes. With less densely packed rings, the tree stem is more susceptible to uprooting and snapping from wind (Doyle et al. 1995).

More importantly for this study, a few studies examine the effects of hurricanes on coastal tree growth. One such study shows that tree growth actually increased following a hurricane occurrence (Rodgers III et al. 2006). The explanation for this was that the hurricane was so damaging that when the weakest trees died during the hurricane, those trees that did survive took advantage of the lack of competition. However, this result is contradictory to previous studies in a few ways. First, the trees used in Rodgers III et al. (2006) were the largest trees in the stand. These would not have been the trees to take advantage of the lack of competition because they would not have been affected by competition initially. Second, it has been noted that the largest trees are the most affected by high winds (Curtis 1942; Doyle et al. 1995; Earley 2004; Francis and Gillespie 1993). High winds are expected to affect growth because of loss of limbs and leaves. Instead of the tree concentrating energy on stem growth, it must first repair itself. This means that the trees used in that study would have been the most negatively affected by hurricanes. Finally, this result does not follow principles of fresh water availability to the trees. During these hurricanes, salt water from the storm surge inundate the area, and Rodgers III et al (2006) did not analyze the effects of storm surge. Salt water tolerance for these trees is low and likely detrimental to tree growth (Conner et al. 1997; Pezeshki et al. 1990). As partial motivation for this study, it is assumed that the effects of data manipulation during statistical processing of the raw tree ring widths affected the results of the Rodgers et al. (2006) study.

1.2 Research Objectives

The Mississippi Gulf Coast is an active region for hurricanes (Keim et al. 2007). The five most economically impactful, socially remembered, and highest magnitude hurricanes in the past 70 years made landfall near Pascagoula, MS and include the 1947 Hurricane, Hurricane Camille (1969), Frederic (1979), Georges (1998), and Katrina (2005). These hurricanes created storm surges that impacted numerous forested areas along the northern Gulf of Mexico Coast, including the Pearl River Wildlife Management Area, Grand Bay National Estuarine Research Reserve, and

Weeks Bay National Estuarine Research Reserve. This combination of coastal forests and frequent intense hurricanes provides a place to study the relationships between hurricanes and tree growth.

No method has yet been described as a “best practice” for studying relationships between trees and hurricanes. This study furthers the knowledge for the relationship between hurricanes and tree growth to one day improve the known record of hurricanes in future studies. A master chronology of tree growth is formed from slash pine trees growing within three kilometers of the Gulf of Mexico in southern Mississippi. It is expected that the trees in this area will grow less the year immediately following a hurricane because most hurricanes make landfall in this area after the growing season of the trees. Less than normal (mean) tree growth is expected because of wind-damaged branches and leaves, and salt-water inundation from storm surge. Research objectives are as follows:

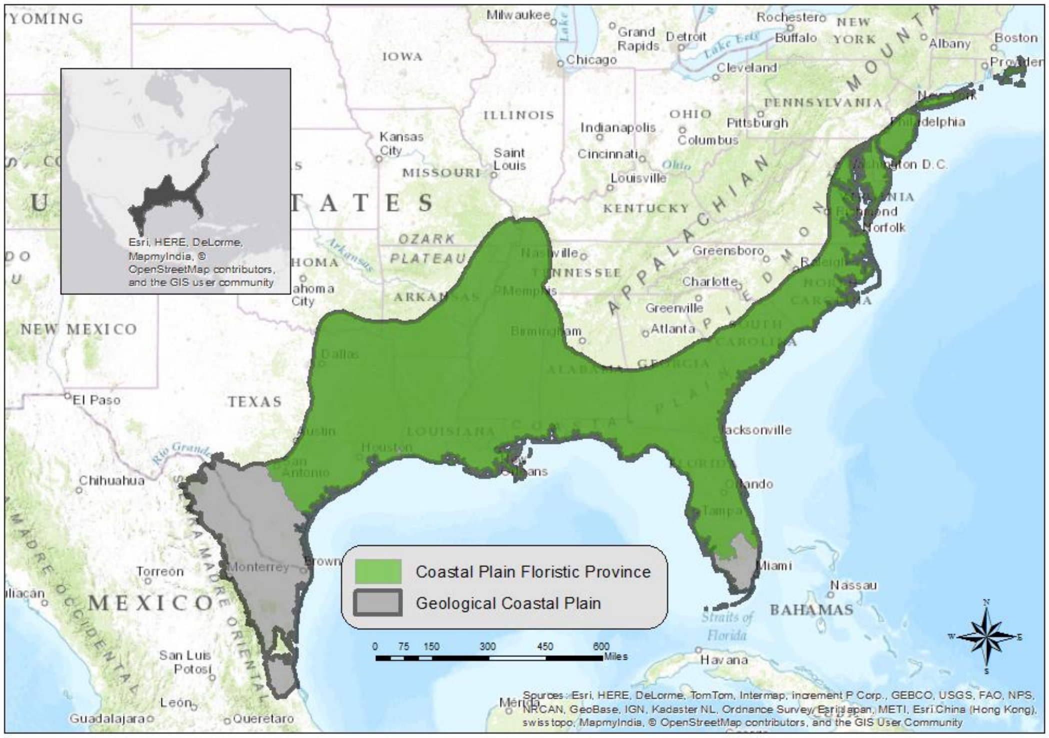
1.) Find an efficient field method for identifying trees most affected by hurricanes.
2.) Analyze growth rings for their relationship to hurricanes.
3.) Analyze growth rings for their relationship to annual climate.

Correlating these tree proxy data with known hurricane occurrences allows for expansion in dendrotempestology, the study of tropical storms using tree rings. Field methods and data used in this study are new to both dendrochronology and hurricane climatology, and these methods can be applied to future dendrotempestological research. If a relationship exists between tree growth and hurricane occurrence, then trees older than the historical hurricane record can be used to extend the current hurricane record. Additionally, damage from hurricanes can also be better understood if one hurricane variable correlates better to low tree growth than another. Lastly, experimental design is important to this research. Likely, trees closest to the coast will be affected by storm surge, and trees further inland will be more affected by wind. After a relationship is found, dendrotempestology can expand into these deeper topics.

2. DATA AND METHODS

2.1 Study Area

The North American Coastal Plain (NACP) is a geologically similar landscape that stretches from southern Texas along the Gulf of Mexico to New England adjacent to the Atlantic Ocean (Figure 1) (Noss et al. 2014). The NACP is comprised of fluvial and marine sediments deposited in the last 60 million years and covers over 1 million km^2. It contains more than 1,800 endemic species of vascular plants and is recognized as a biodiversity hotpot (Noss et al. 2014).



Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 1: A map of the North American Coastal Plain comprised of the Coastal Plain Floristic Province and the Geological Coastal Plain

The NACP is home to a similar climatic landscape and is considered humid subtropical according to the Köppen climate types. In general, it receives plenty of precipitation and few days with freezing temperatures. This makes the NACP a prime location for forest growth. Hurricanes also occur in this area frequently. This means that many coastal locations in the NACP would be prime areas for the study of dendrotempestology.

Trees for this study are found in a pine savanna/salt marsh habitat in coastal Mississippi in a reserve known as the Grand Bay National Estuarine Research Reserve (GBNERR) (Figure 2). Pine tree species are well studied in respect to tree-climate relationships (Henderson and Grissino-Mayer 2009; Platt 1999). GBNERR lies in an area heavily impacted by hurricanes in the past century (Keim et al. 2007).

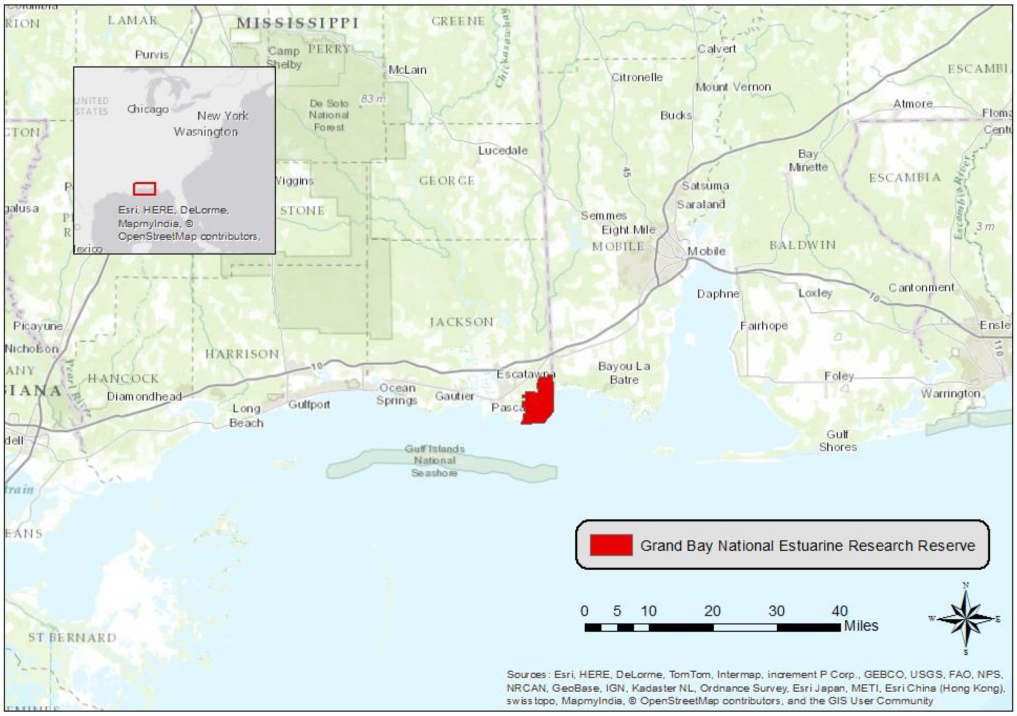


Figure 2: A map showing Grand Bay National Estuarine Research Reserve in red.

GBNERR is one of 28 stations around the United States used to monitor coastal and estuarine resources. GBNERR is located near the center of the NACP in coastal Mississippi. It is a unique pine savanna/salt marsh habitat covering 7,284 hectares of southern Mississippi (Hilbert 2006). Though pine trees are ubiquitous throughout GBNERR, pine trees closest to the coast grow on areas known as salt panne islands. Personal, visual analysis of the landscape reveals that the pine trees growing close to the coast only grow on the highest lands capable of supporting a fresh water table. Often, it appears that the lowest grounds are ancient tidal creeks and relict riverbeds.

Any plants growing on the islands suffer from periodic saltwater inundation, and as the islands sink and shrink from saltwater inundation and sediment compaction, the flora disappear. Figure 3 shows the dynamic morphology of salt panne islands: the island at the top left (1) is still relatively healthy as compared to (2), whose vegetated area has shrunken significantly. Island (3) is completely void of vegetation and is now a salt bed due to high salinity levels in the soil. Dead trees and tree stumps can be found in places where the soil has completely bleached showing that vegetation dies near the edges of salt pannes. These salt pannes are similar to the forest resource islands described in the Everglades National Park in southern Florida (Ross and Sah 2011).

GBNERR was established as a National Estuarine Research Reserve in 1999 as a result of the Coastal Zone Management Act of 1972 (Hilbert 2006). Before this time, a small homestead existed at the northern end of the NERR. National buy-backs of the land to be set as a NERR were begun in 1993. Some private holdings still remain within the main boundaries o GBNERR: three temporary housing establishments used as fishing camps, a boat launch, a small number of permanent houses, and a firing range. However, since the mid-1900s, much of Grand Bay has been undisturbed by human activity. This makes GBNERR a suitable area for ecological studies.

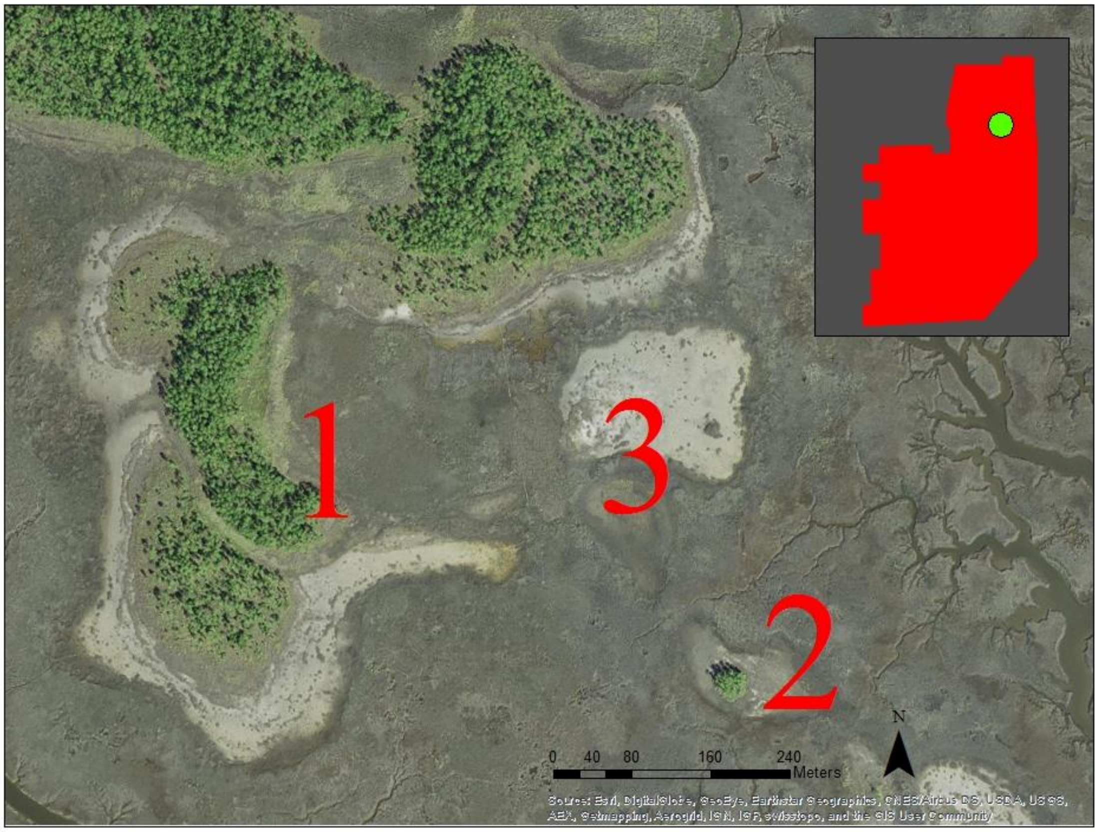


Figure 3: An image showing the different stages of a salt panne island at the southern end of the pine savannas in GBNERR: (1) is a healthy, vegetated salt panne, (2) is vegetated, but degraded from stage 1, and (3) is now void of vegetation. The inset is the boundaries of GBNERR with this site in green.

Unfortunately, many of the trees in GBNERR do not exceed 100 years old (pre-1920s). Therefore, extending the known record with this area is not possible, but the relationship can be established. Aerial photographs from 1942 show little vegetation in this area (Figure 4a). Additionally, aerial photographs from 1952 show an increase of trees in the area as compared to the 1942 photographs. These images also show the contrast between areas with and without trees. The trees are much darker than the rest of the landscape. Most of GBNERR did not have large pine trees present during this time. This could be the result of two possible factors: (1) at this time

GBNERR was more of a grassland than a pine forest and that with time, vegetation became denser, and/or (2) logging and turpentine industries had a dramatic effect at GBNERR (Platt 1998). Turpentine drip pans (used to extract resin from trees, which was distilled to create products such as turpentine, soaps, and candles) have been found in various places around GBNERR (personal observation). A few trees cored at GBNERR contain areas within the rings (ca. 1915) of narrow ring widths and darkening of tree rings due to high resin production, two indicators of turpentine-activity stress (Grissino-Mayer et al. 2001).

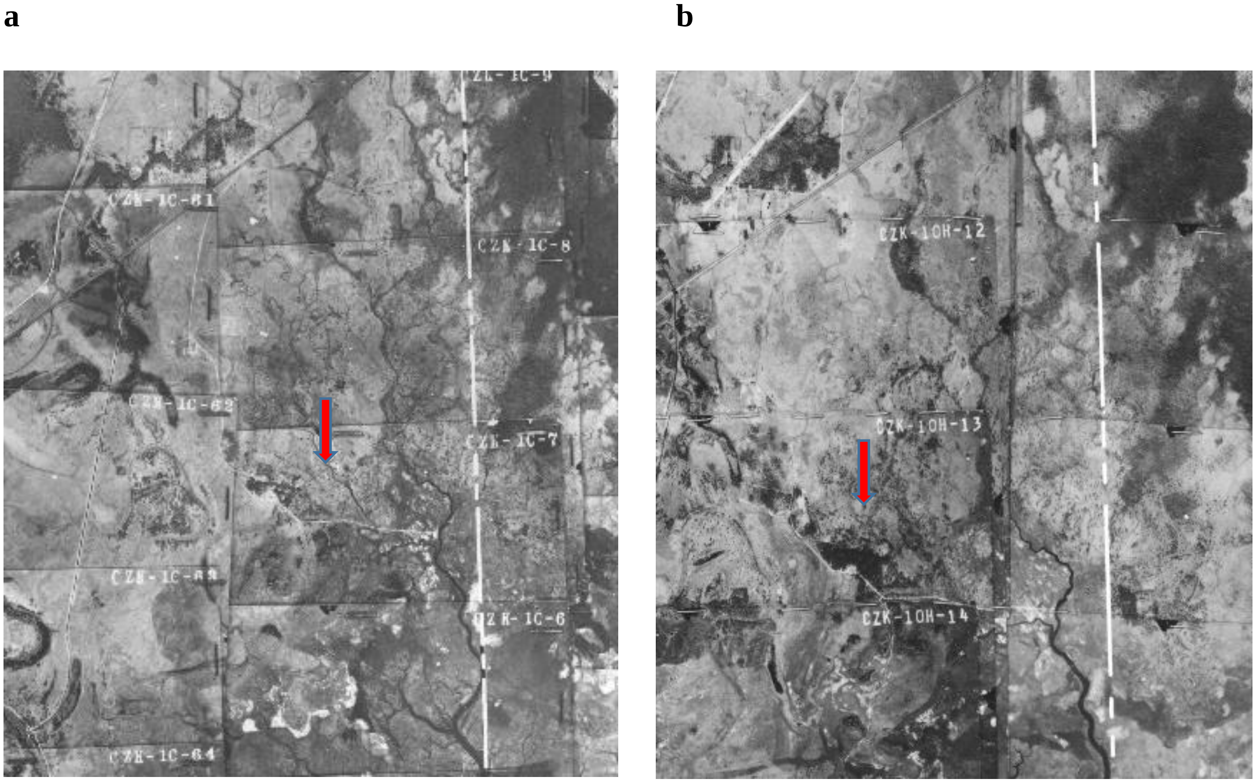


Figure 4: Historical images of GBNERR, courtesy of the Cartographic Information Center at LSU. Figure 4a was taken in 1942. Figure 4b was taken in 1952. The white dotted line is the Mississippi-Alabama state line for reference. The red arrows point at a similar location in each image. In 4b, the red arrow points at a group of newly grown trees not present in 4a.

Two species of pine tree can be found at GBNERR: *Pinus elliottii* var. *elliottii* (slash pine) and *Pinus palustris* (longleaf pine), the former being more common. Few other canopy tree species exist in GBNERR and the most common are *Taxodium ascendens* (pond cypress), *Acer rubrum* (red maple), *Magnolia virginiana* (sweetbay magnolia), *Nyssa biflora* (swamp tupelo), and the invasive *Triadica sebifera* (Chinese tallow).

The most common grass in GBNERR is *Spartina patens* (salt marsh hay). Though fires are an important part of pine savanna habitats (Glitzenstein et al. 1995), since GBNERR was a homestead for many decades, fire has not been prevalent in the area evidenced by a lack of fire scars found in the tree cores used in this study. The understory shrubs (most commonly gallberry (*Ilex coriaceai*), wax myrtle (*Myrica cerifera*), and swamp titi (*Cyrilla racemiflora*)) are overgrown due to the lack of fire. Other species, found more commonly in salt marshes, are also common across GBNERR, especially in low lying areas such as deserted riverbeds, tidal estuaries, and intermittently-flooded bogs. These species include, but are not limited to, *Juncus roemerianus* (black needlerush), *Typha latifolia* (broadleaf cattail), and *Cladium jamaicense* (sawgrass) (Brown 2007).

2.2 Tree Ring Field and Laboratory Methodology

An initial analysis by this study found trees closest to the coast showed signs of sensitivity in their growth rings when compared to inland trees. Figure 5 shows two cross sections from trees at GBNERR. The top cross section was taken from a tree near the coast and the bottom cross section was taken approximately 1 km inland. The coastal cross section dates to 1922 and is 30 cm in diameter. The inland cross section dates to 1962 and is 56 cm in diameter, thus the coastal tree is older and smaller. For this reason, tree cores were obtained from trees closest to the coast where they receive the most stress.

Figure 5: Cross sections from a tree nearest to the coast (top) and further inland (bottom). The inland tree grows nearly three times more per year than the coastal tree.

Figure 6 shows the location of the 30 trees cored for this study. Older trees are desirable for this study to find the relationship with tree growth with as many hurricanes in the record as possible. Trees were chosen for their large size and aged appearance (flat tops, knotted trunks, curved branches, and lack of smaller canopy branches (Pederson 2010)). 90 cores were recovered from 30 trees using a 16-inch Haglof increment borer at breast height (1.3 m) in June 2015. Three cores were extracted at 90°, 180°, and 270° bearing around the stem from each tree for proper crossdating techniques (Stokes and Smiley 1968). Cores were placed in paper straws and labeled using consecutive tree numbers and the abbreviated method of species naming (e.g. *Pinus elliottii*

= PIEL). Table 1 has a list of the trees, their diameter at breast height (DBH), and their latitude and longitude.

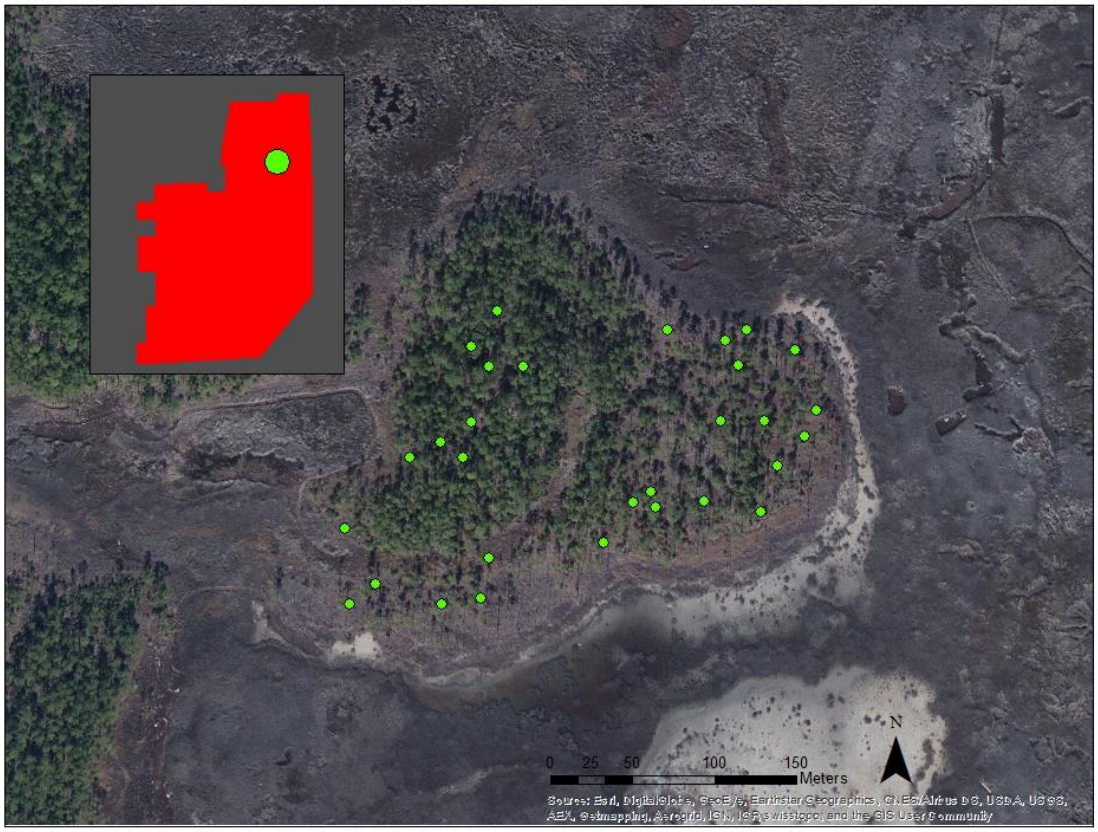


Figure 6: A map of the site used in this study with locations of the cored trees in green. The inset is the boundaries of GBNERR with this site in green.

Crossdating is especially important for insuring proper dating of each year of the tree ring chronology and for insuring accurate annual resolution (Speer 2010). Accurate crossdating is necessary for analyzing tree rings to climate. All cores were glued and mounted into wooden core mounts and sanded using sandpaper in a succession of increasing grit sized (ANSI 120, 220, 320, and 400) (Stokes and Smiley 1968). The cores were visually crossdated using the list method, scanned and measured using the computer software WinDENDRO to the nearest 0.001 mm, and assessed for quality crossdating using the computer program COFECHA (Grissino-Mayer 2001; Holmes 1983; Yamaguchi 1991).

Table 1: List of the trees shown with field number, species (PIEL = *Pinus elliottii*), diameter at breast height in inches (DBH), and location.

Tree Number	**Tree Species**	**DBH (inches)**	**Latitude**	**Longitude**
1	PIEL	16.0	30.401333	-88.412194
2	PIEL	13.6	30.401472	-88.412111
3	PIEL	14.2	30.401167	-88.412361
4	PIEL	15.5	30.401806	-88.412250
5	PIEL	15.3	30.400917	-88.412472
6	PIEL	14.6	30.400972	-88.412833
7	PIEL	12.9	30.401917	-88.412556
8	PIEL	14.3	30.401917	-88.413056
9	PIEL	14.6	30.402028	-88.414139
10	PIEL	13.1	30.401833	-88.414306
11	PIEL	14.1	30.400750	-88.413472
12	PIEL	10.3	30.400444	-88.414250
13	PIEL	12.1	30.400417	-88.414500
14	PIEL	10.8	30.400528	-88.414917
15	PIEL	11.5	30.400417	-88.415083
16	PIEL	17.8	30.400944	-88.413139
17	PIEL	14.2	30.400972	-88.413278
18	PIEL	16.0	30.401028	-88.413167
19	PIEL	13.3	30.401722	-88.413972
20	PIEL	20.1	30.401722	-88.414194
21	PIEL	13.9	30.400833	-88.415111
22	PIEL	14.0	30.401222	-88.414694
23	PIEL	18.1	30.401306	-88.414500
24	PIEL	16.9	30.401222	-88.414361
25	PIEL	18.2	30.401417	-88.414306
26	PIEL	11.6	30.400667	-88.414194
27	PIEL	17.1	30.401417	-88.412444
28	PIEL	12.8	30.401417	-88.412722
29	PIEL	13.6	30.401722	-88.412611
30	PIEL	10.9	30.401861	-88.412694

Trees are biological organisms, and as such, they do not all grow at the same rate even in the same environmental setting. Trees must follow similar patterns before they can be analyzed against climate parameters. To determine the intercorrelation in a group of tree cores (also known as series), measurements are assessed for quality using the computer program COFECHA, a program designed specifically to output a series intercorrelation from measured raw tree-ring widths. If the trees grow following a similar pattern, the series intercorrelation will be 100%, or 1.0. A desirable intercorrelation for a master chronology is above 0.4 (Holmes et al. 1986).

To achieve the highest series intra- and intercorrelation possible and best possible master chronology for climate analysis, then optimal tree cores (e.g. cores with bark, cores without breaks in the wood, cores with limited false or missing rings, etc.) should be used. To ensure that trees respond similarly at an individual level, an intracorrelation analysis was performed on each tree core. Tree core A was analyzed against tree core B for each tree. If a tree core shows a negative correlation with its partner tree core, this means that the tree is growing completely differently on the two sides of the tree. The average intracorrelation for trees used in this study was $r = 0.747$. This suggests the trees are growing similarly on both sides. Forty-five tree cores representing 15 trees were chosen to be used in COFECHA.

After the raw ring width measurements were crossdated, a master, or indexed, chronology was formed for total, latewood, and earlywood ring widths using the computer program ARSTAN (Holmes et al. 1986). Tree-ring widths decrease naturally over time because as the tree's circumference increases with each year, and the volume of wood produced typically stays the same ideally, then the diameter of the tree that year must decrease each subsequent year (Fritts 1976). ARSTAN allows the user to define and detrend this growth trend for each series interactively. The best fit for the trees used in this study was a 67% detrending spline, a commonly used detrending method in dendrochronology (Cook and Kairiukstis 1990; Holmes et al. 1986). A 67% spline is used to remove growth effects in each series. This spline removes the trend found using a moving window sized at 67% of each series' age.

ARSTAN also calculates the expressed population signal (EPS) which assesses the statistical quality of the mean chronology versus a theoretical noise-free chronology and is commonly used in proxy analysis (DeLong et al. 2007; Wigley et al. 1984). Ultimately, the higher the interseries correlation (*r*) of a sample, the fewer series (N) are needed for further comparative analyses. An arbitrary value of ≥ 0.85 was determined to be acceptable for increasing the signal-to-noise ratio (Briffa 1995; Wigley et al. 1984). For this study ($r = 0.677$), the amount of records needed to keep EPS ≥ 0.85 is approximately N = 3. The master chronology used in this study is sufficient for analysis to 1930. Prior to 1930, there are too few series to accurately assess the relationship between tree growth at this site to climate data.

2.3 Climate Data

The GBNERR region has a subtropical climate with hot wet summers and cool dry winters. The closest site to GBNERR analyzed by the study of Keim et al. (2007) is Dauphin Island, AL, approximately 32 km away. The return period for major hurricanes at Dauphin Island is 21 years. According to the data archived by Southern Regional Climate Center, average annual precipitation (1940 – 2014) is over 1500 mm, more than 500 mm in June to August alone. The average January temperature is 10.2°C while the average July temperature is 27.4°C. Due to low-pressure fronts passing north of GBNERR, winds most commonly come from the south, often bringing warm, moist air (and, in turn, afternoon thunderstorms) during summer, known as a "Gulf Return" pattern (Muller 1977).

Though annual climate is an important quality for tree growth, the hypothesis for this study is that years with intense hurricanes will cause low growth in trees. It is expected that the largest magnitude hurricanes will affect trees the most. One way to measure the magnitude of hurricanes is by the size of their storm surge. SURGEDAT is a hurricane storm surge database operated by Drs. Harold Needham and Barry Keim at LSU. The SURGEDAT database includes storm surge estimates as far as the 1880s for the Atlantic Hurricane Basin (Needham and Keim 2012; Needham et al. 2013).

A 45 km radius was chosen because this circle represents the area of a large metropolitan area (Needham 2014). Factors that may influence the flooding caused by hurricanes include, but are not limited to, wind, rainfall, atmospheric pressure, bathymetry, waves, river flow, and tides (Irish et al. 2008). Therefore, the magnitude of a storm surge at landfall can change dramatically with increasing distance from the center of its associated hurricane. A storm surge must be called a “storm tide” because it includes both the hurricane-induced surge and tide levels (Needham 2014). Occasionally, tides can be removed from the data, and in that case, a surge is provided. Table 2 includes hurricane storm surges from SURGEDAT recorded for all storms within a 45 km radius of GBNERR. It includes the storm name, its year of occurrence, measurement location, magnitude, and rank among the other storm surges.

Since the largest storm surges will affect tree growth the most, the five largest storm surges are listed here. Hurricane Isaac would be the fourth largest record. However, these trees were cored in 2015, and there are only two full years of growth following that event (2013 and 2014). Therefore, any delayed or sustained suppression is likely not yet recorded, so it is omitted in this top five list. The top five, in order from largest to smallest are (1) Hurricane Katrina, 2005, 7.9 m,

(2) Hurricane Camille, 1969, 4.7 m, (3) the Unnamed Hurricane of 1947, 3.66 m, (4) Hurricane Frederic, 1979, 3.20 m, and (5) Hurricane Georges, 1998, 2.90 m.

High winds caused by hurricanes are also expected to have an impact on the growth of trees. The National Hurricane Center (NHC) supplies a hurricane database (HURDAT) that includes weather observations for hurricanes as far back as 1851. HURDAT contains maximum wind speeds (knots), central air pressure (millibars), dates, and latitude and longitude for U. S. land-falling hurricanes (Jarvinen et al. 1984).

Table 2: Hurricanes that produced a recorded storm surge within a 45 kilometer radius of GBNERR. Surges are listed as the maximum surge record within the radius. *Hurricane Isaac is not included in the rank because it occurs at the end of the tree-ring series.

Name	Month/ Year	Latitude	Longitude	Distance from GBNERR (km)	Surge Height (m)	Rank
Unnamed	9/1947	-88.88	30.39	47.29	3.66	3
Unnamed	9/1948	-88.93	30.39	47.29	1.81	11
Unnamed	9/1949	-88.88	30.39	42.98	1.33	16
Brenda	8/1955	-88.93	30.39	47.29	1.83	10
TS #1	6/1956	-88.88	30.39	42.83	1.42	13
Hilda	9/1964	-88.85	30.38	40.17	1.40	15
Betsy	9/1965	-88.56	30.34	12.11	2.24	8
Camille	8/1969	-88.39	30.41	9.50	4.70	2
Frederic	9/1979	-88.32	30.40	12.78	3.20	4
Danny	8/1985	-88.25	30.38	17.70	0.50	19
Beryl	8/1988	-88.88	30.39	42.98	1.10	17
Chantal	8/1989	-88.88	30.39	42.98	0.75	18
Georges	9/1998	-88.52	30.34	7.84	2.90	5
Isidore	9/2002	-88.85	30.38	40.28	2.08	8
Bill	7/2003	-88.85	30.38	40.29	1.41	14
Ivan	9/2004	-88.56	30.36	11.99	2.05	9
Katrina	8/2005	-88.55	30.35	11.30	7.90	1
Gustav	9/2008	-88.51	30.35	6.73	2.49	6
Lee	9/2011	-88.87	30.40	42.10	1.50	12
Isaac	8/2012	-88.42	30.48	14.59	4.11	*

Best-track storm positions from HURDAT are noted at 6-hourly intervals. Some inherent issues exist with the database that has changed its record keeping with time: accuracy in the early part of the record (Landsea et al. 2004) and intensity inaccuracies (Landsea and Franklin 2012). However, these are not major issues for this study. First, the trees used in this study do not pre-date the issues encountered for hurricanes occurring between 1851 to 1910. Second, while intensity likely plays a role in the effects on coastal trees, it is assumed that small differences in wind speeds are likely not to have a large effect on annual tree growth.

This study uses the maximum wind speed measurement for each hurricane passing within 120 km of GBNERR from HURDAT between 1940 to 2014 (Table 3). This distance was chosen because it is half of the radius of maximum hurricane strength winds ($\geq$33 ms^{-1}) (Keim et al. 2007). These hurricane strength winds are defined in the Saffir-Simpson hurricane wind scale (SSHWS), a commonly used scale used to define hurricane intensities. The SSHWS was created in 1969 to standardize the vocabulary used to describe hurricanes (Simpson and Saffir 1974). It divides hurricanes into five categories by wind speed with increasing intensities: (1) 33 – 42 ms^{-1}, (2) 43 – 49 ms^{-1}, (3) 50 – 58 ms^{-1}, (4) 58 – 70 ms^{-1}, and (5) $\geq$ 70 ms^{-1}. A major hurricane is defined as category 3 or higher.

Wind speeds, driven mostly by pressure gradients, can remain similar in a much larger radius than storm surge within a hurricane. For example, Keim et al. (2007) note that the radius of hurricane force winds in a major hurricane can extend as much as 240 km. The maximum winds recorded for each hurricane within the record were found using the computer program R For Statistical Computing (Elsner and Jagger 2013; R Development Core Team 2011). For this study, hurricanes that tracked at any point within 120 km within GBNERR were counted. The highest wind speed for each hurricane was then recorded. Table 3 includes these wind speeds, year of occurrence, measurement location, magnitude, and rank among all the wind speeds.

Often, more than one hurricane would occur in a given year. When this occurred, the maximum wind speed used was either (1) an average of the maximum wind speeds for all hurricanes affecting the site that year (if all maximum wind speeds were within 10 ms^{-1} of each other), or (2) the maximum wind speed of all hurricanes that year. This decision is the result of the assumption that one strong hurricane will exacerbate or outweigh any effects of a much smaller hurricane. For example, in 2005, Hurricane Dennis produced wind speeds of 33 ms^{-1} at GBNERR. Two months later, Hurricane Katrina produced wind speeds of 56 ms^{-1} in GBNERR. It is assumed that any damage caused by Dennis was overshadowed by Katrina. It is also assumed in this study that compound effects from multiple hurricanes in one year is not as important as the fact that a hurricane impacted the site. Thus, only one hurricane was included per year.

The five highest wind speeds at GBNERR in order from largest to smallest are as follows: (1) Hurricane Camille, 1969, 72.02 ms^{-1}, (2) Hurricane Carmen, 1974, 66.87 ms^{-1}, (3) Hurricane Andrew, 1992, 65.48 ms^{-1}, (4) Hurricane Betsy, 1965, 63.72 ms^{-1}, and (5) Hurricane Frederic, 1979, 59.16 ms^{-1}. Two of these five hurricanes (Camille and Frederic) were also in the top five largest storm surges at GBNERR.

The goal of this study is to determine the relationship between hurricanes and tree growth. However, tree growth is not only determined by hurricanes. Annual climate is also very important for the growth of these trees. The Palmer Drought Severity Index (PDSI) is commonly used for climate analysis and tree growth (Meko et al. 1993; Stockton and Meko 1975) because it takes into account precipitation, evapotranspiration, and soil moisture conditions (Alley 1984; Palmer 1965), all of which are important to tree growth. To analyze these parameters, the PDSI computational method uses precipitation and temperature measurements to calculate evapotranspiration and groundwater recharge rates because precipitation provides water and the evaporative effects of high temperatures remove water (Alley 1984). When precipitation is high and temperature (evaporation) is low, the PDSI value is positive (phase) because there is a net positive balance in the water budget. PDSI is in a negative phase when precipitation is low and temperature is high.

To determine any effects of annual climate on the tree growth at GBNERR, monthly PDSI data were retrieved for years 1940 – 2014 from the National Climatic Data Center (NCDC) website for Climatic Division 10 of Mississippi that represents the three coastal counties of Mississippi including Hancock, Harrison, and Jackson Counties (Karl and Koss 1984). GBNERR lies in Jackson County, MS.

In the following chapter, both the indexed chronology and raw ring widths will be compared to these climatic variables (hurricane storm surge, hurricane winds, and monthly PDSI). Various statistical methods will be used to best determine the relationship between hurricanes and tree growth, all the while assuming that these coastal physical processes involved will cause tree growth to decrease following a hurricane.

Table 3: Hurricanes that produced a hurricane force wind speeds within a 120 km radius of GBNERR. Surges are listed as the maximum surge record within the radius. *Hurricane Isaac is not included in the rank because it occurs at the end of the series.

Name	Month/ Year	Latitude	Longitude	Maximum Wind Speed (ms^{-1})	Rank
Unnamed	8/1940	28.70	-90.63	40.21	17
Unnamed	9/1947	29.40	-89.00	48.87	11
Unnamed	9/1948	29.28	-90.40	35.57	22
Baker	8/1950	29.40	-88.20	38.58	18
Florence	9/1953	28.7	-87.00	46.30	14
Flossy	9/1956	30.00	-87.50	41.15	15
Ethel	9/1960	29.10	-88.90	41.15	15
Betsy	9/1965	28.72	-89.67	63.72	4
Camille	8/1969	29.40	-89.00	72.02	1
Agnes	6/1972	28.29	-85.70	38.58	18
Carmen	9/1974	28.70	-90.80	66.87	2
Eloise	9/1975	29.48	-86.56	58.77	6
Frederic	9/1979	29.70	-88.00	59.16	5
Elena	9/1985	29.70	-87.30	54.01	10
Florence	9/1988	28.70	-89.30	36.01	20
Andrew	8/1992	28.71	-90.79	65.48	3
Opal	10/1995	29.00	-87.70	56.58	7
Danny	7/1997	29.70	-89.0	36.01	20
Georges	9/1998	28.80	-88.30	48.87	11
Barry	8/2001	30.02	-86.22	33.64	24
Ivan	9/2004	28.90	-88.20	56.58	7
Katrina	8/2005	29.90	-86.90	56.58	7
Gustav	9/2008	28.80	-90.30	48.87	11
Ida	11/2009	28.77	-88.70	33.98	23
Isaac	8/2012	28.90	-89.40	36.01	*

3. RESULTS AND DISCUSSION

The first goal of this study is to assess the relationship between the indexed master chronology to hurricane characteristics similar to Rodgers III et al. (2006). These methods will later be compared to methods using raw ring widths and a suppression chronology. To assess the relationship between tree-ring width and hurricanes characteristics, correlation tests and linear regression models are used. Data are analyzed for normality, and the time series of storm surge and wind are discussed. For the first part of these results, only the total ring width chronology is used so that the results of this study can be compared to the results of Rodgers et al. (2006).

3.1 Indexed Chronology and Hurricanes

The final chronology for the total ring width was formed for years 1909 – 2014 (106 years), using 30 dated series with a series intercorrelation (*r*) of 0.677 and mean sensitivity of 0.437. A final chronology was also created for latewood (*r* = 0.613) and earlywood (*r* = 0.655) for the same time span and the same number of dated series. Figure 7 depicts the indexed chronologies with the number of series for each year for total (green), latewood (red), and earlywood (blue) ring widths. The number of trees increases with year because trees live for a finite amount of time. Therefore, old trees are uncommon relative to young trees. A quick recruitment of trees in the 1950s and 1960s is present in this record shown by increases in the number of series used in Figure 7 during those time periods.

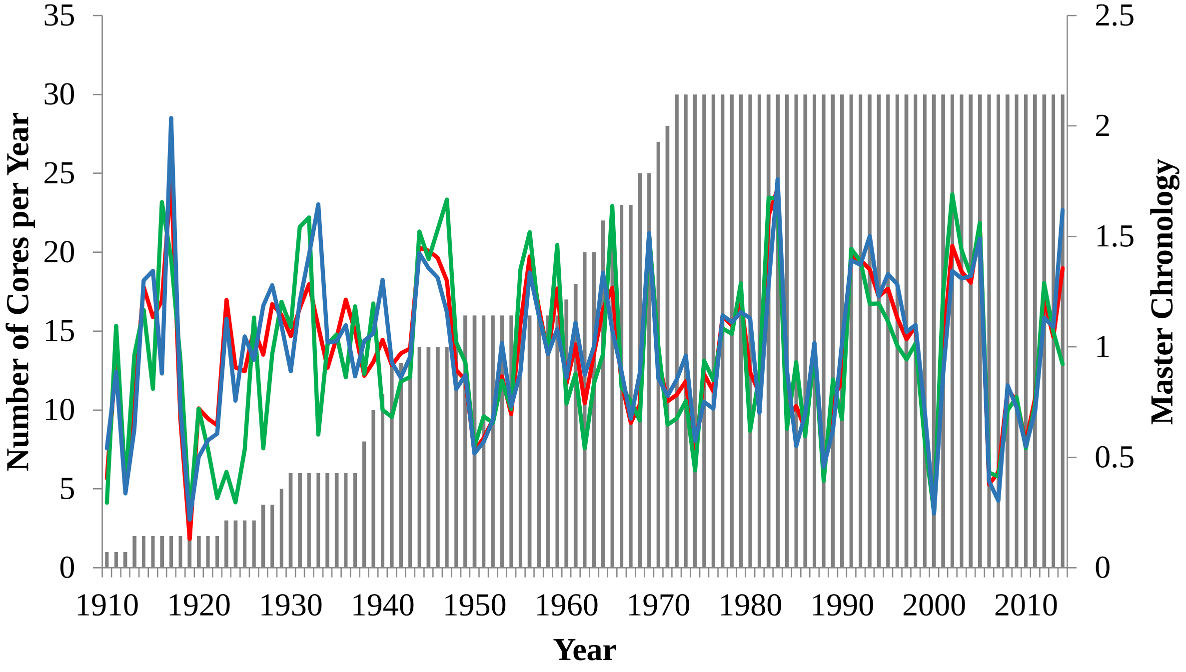


Figure 7: Number of cores per year used in this study (black bars) with an overlay of the indexed chronologies used in this study. Total ring width is in green, latewood in red, and earlywood in blue.

The master chronology used in this study visually shows decreases following substantial hurricane occurrences (Figure 8). Figure 8 is the GBNERR master chronology for (a) total ring widths, (b) latewood, and (c) earlywood plotted with major hurricanes that impacted the site. On figure 8, major hurricanes (windspeeds $\geq$ 50 ms^{-1}) are plotted as vertical lines for comparison. Upon further inspection of the total ring width index and hurricane occurrences (Figure 8a), in most instances, the ring width decreases after a major hurricane. Large decreases in growth directly follow large hurricane years (e.g. 1965, 1969, and 2005). Smaller decreases in growth follow smaller hurricane occurrences (e.g 1985, 1995, and 2008). Two years of low growth do not correspond with major hurricane occurrences (the late 1980s and 1999/2000). However, the late 1980s were accompanied with numerous smaller hurricane occurrences, and 1998 experienced one hurricane that tracked close to GBNERR (Hurricane Georges).

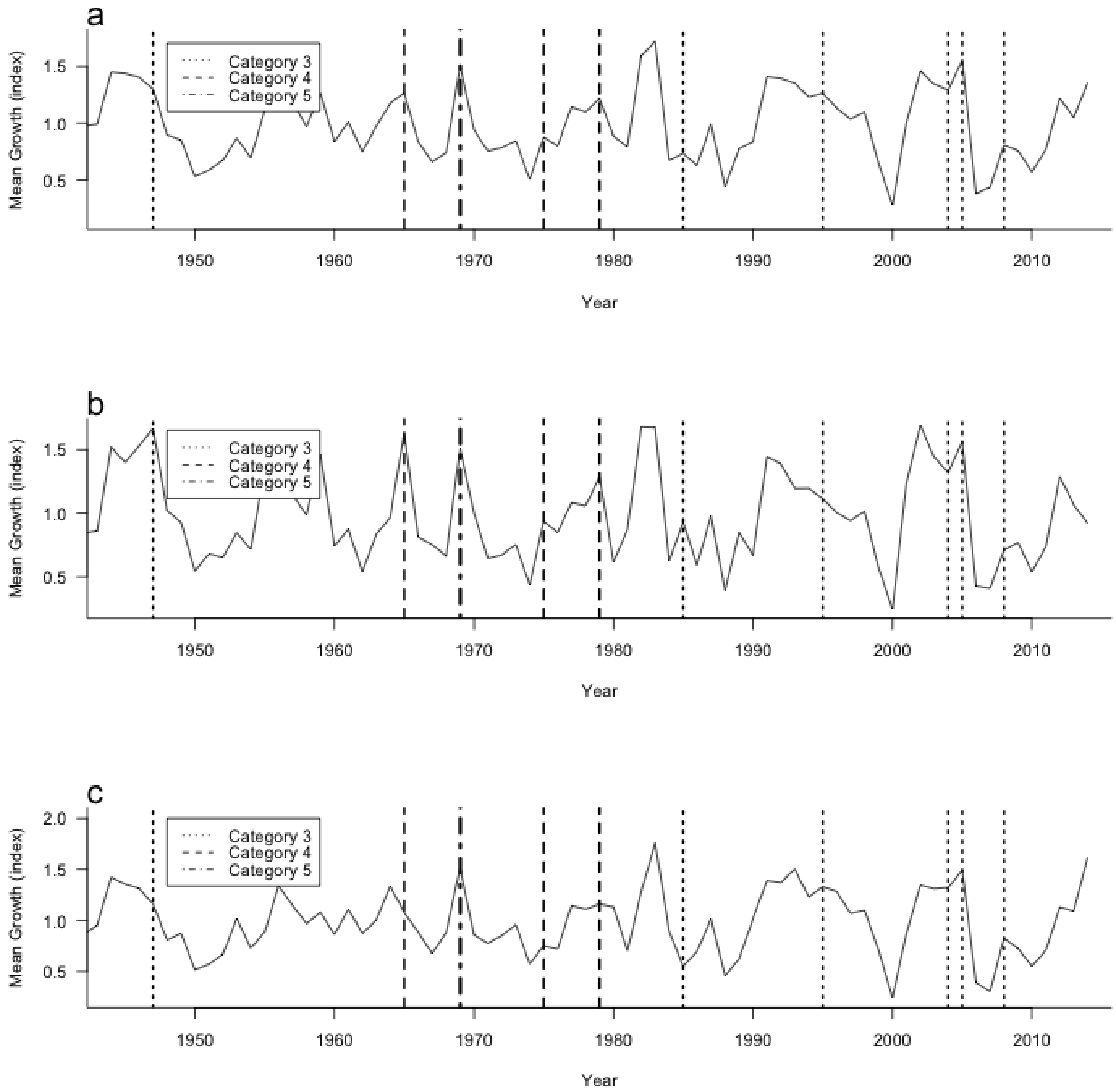


Figure 8: Final (a) total, (b) latewood, and (c) earlywood tree-ring master chronology indices used in this study. Major hurricanes occurring at GBNERR are plotted as vertical lines.

To begin assessing the relationship between specific hurricane variables and tree growth, storm surge and wind values used in this study are shown in Figure 9a and c, respectively. No significant trend is found in the storm surge or wind speed data, but a horizontal mean line is included to visually differentiate the larger events from the smaller ones. The average storm surge height is 2.51 m and the average hurricane wind speed is 48.55 ms^{-1}.

Figures 9b and d show the master chronology of total ring width plotted with the storm surge and wind speeds, respectively. The largest events coincide with large decreases in the index, especially if a year has both a large wind and large storm surge recorded (e.g. 1969, 1998, and 2005). However, when smaller storms (below the mean value) are compared to the index, it is more difficult to assess a pattern or relationship between growth and hurricane variables due to the influence of other effects. Some interesting results stem from a comparison among the effects of surge versus the effect of winds. Some of the largest wind records (above the mean value of records) occur in the mid-1970s and none of those correspond with similarly large storm surges during the same period. Additonally, the index does not show large decreases in growth during this period, and in fact, increases in growth are seen that correspond with the mid-1970s and the late 21st century. As noted in a previous section, the latest part of the hurricane record (2012 – 2014) cannot be analyzed against multiple years of growth, because only two full years of growth follow 2012. Therefore analyzing the latest part of the index (2012 – 2014) is misleading because those years of analysis have not yet happened.

The study of Rodgers III et al. (2006) notes the index may be sensitive to the frequency of hurricanes and not just to largest events or nearest events. Periods with numerous storm surge and high wind events include the 1980s and the 2000s. These times also experience decreases in growth. However, the late 1990s also experience a decrease in growth that does not coincide with numerous hurricane events, and instead coincides with a single event (Hurricane Georges, 1998). Though growth decreases, a perfect pattern in this record is difficult to determine. Therefore, it is necessary to asses this relationship statistically.

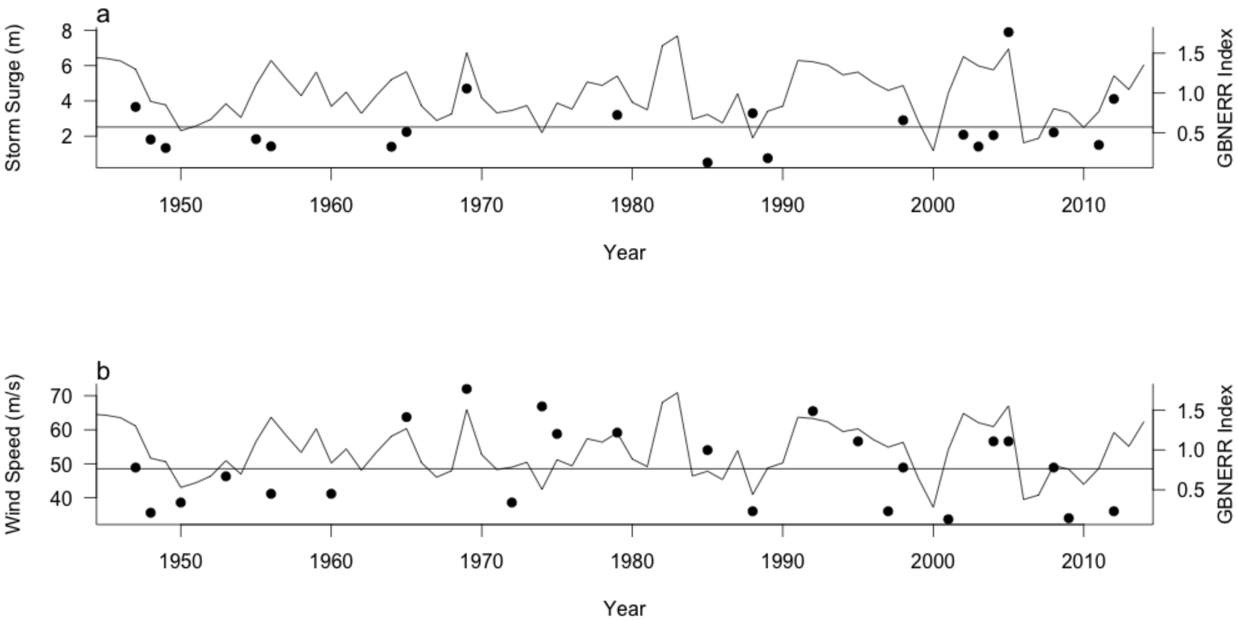


Figure 9: Time series of (a) storm surge and (b) wind speeds used in this study with the mean value of each plotted as a horizontal line. Storm surge and wind are compared with the GBNERR tree-ring width used in this study for comparison.

3.2 Pearson's *r* Correlation and Linear Regression Models

Pearson's product-moment correlation coefficient was used to analyze the strength of these relationships. Pearson's *r* was used for this study because the dependent variable is normally distributed, a linear relationship can be defined between the dependent and independent variables, outliers are minimal, and the data are closely homoscedastic. Homoscedasticity describes a set of variables that have a finite variance. This can be displayed as quantile-quantile (q-q) plots. Figure 10, shows the q-q plots and histograms of the indexed chronology (10a and 10b), the storm surge records (10c and 10d), and the wind speed records (10e and 10f) used in this study. The quantile-quantile plots (Figures 10a, 10c, and 10e), are graphical methods for comparing the distributions of two datasets. The true data points are compared to theoretical data points with an assumed distribution. If the data follow the theoretical data, the points will fall along a straight line when linearly related. The histogram plots (Figures 10b, 10d, and 10f) show the frequency of values occurring in the dataset. A ‘normal’ distribution is characterized by the majority of data occurring near the mean value of the data.

After detrending was applied to the tree-ring chronology in ARSTAN, the data is normally distributed (e.g. theoretical quantiles match sample quantiles (Figure 10a), and the majority of indexed widths occur near the median of the data and decrease toward each end (Figure 10b)). Though the storm surge values are not normally distributed, they do follow an expected pattern with a single peak (Figure 10d). The highest amount of values are biased toward the lower magnitude events and taper off as the magnitude increases. However, the maximum wind histogram (Figure 10f) shows multiple peaks. This is likely due to the fact that the wind values have been applied to a threshold to incorporate only the most extreme wind speeds. This differs from the storm surge threshold that includes all surge events from zero to nearly eight meters. An extreme wind is expected to be different from that of an extreme storm surge value. Storm surge has such a low threshold because any amount of saltwater inundation is considered extreme for the tree, whereas the tree frequently experiences wind.

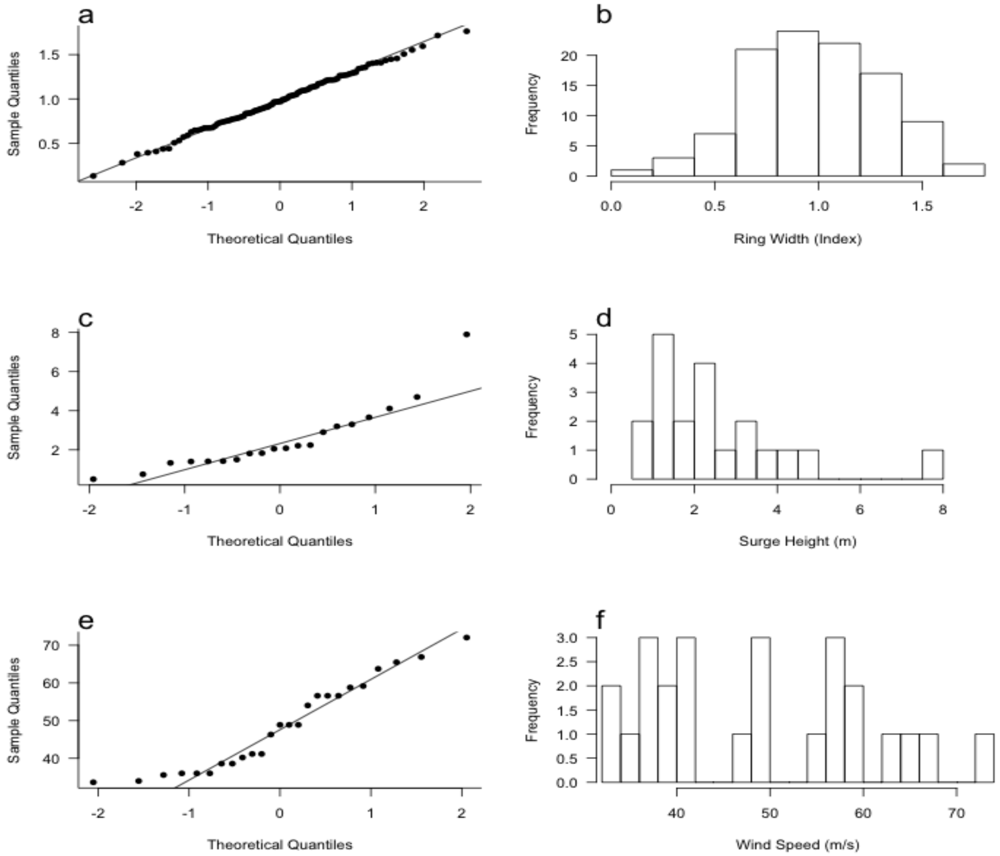


Figure 10: The q-q plots and histograms of the (a and b) tree-ring index, (c and d) storm surge and (e and f) wind speed records used in this study.

Significant results for this study were those results that passed the 95th percentile confidence interval ($p \leq 0.05$). Four years of growth are compared to the hurricane variables: the same year as hurricane occurrence plus the following three consecutive years. This is done to assess when, if any, the decrease in growth occurs. Similar to Rodgers et al. (2006), no relationship was found to be significant. However, as noted previously that decreases in growth seem to correspond with the larger events. Pearson's *r* was then used to determine if the largest events have any effect on the indexed chronology. Those storm surge and wind events greater than the mean were then analyzed against the GBNERR index. Table 4 shows results for Pearson's *r* for the indexed chronology versus the larger (a) storm surge and (b) wind values. A significant relationship was found between storm surge and the following year of growth. The relationship is moderately strong and negative (*r* = -0.604).

Table 4: Degrees of freedom (df), correlation coefficients (*r*), and *p*-values for tests using ring width versus storm surge (a) and wind speed (b) values above the mean.

a (storm surge)					**b (wind speeds)**			
Test	df	*r*	*p*-value		Test	df	*r*	*p*-value
Same Year	9	0.377	0.253		Same Year	11	0.169	0.581
1 Year Lag	**9**	**-0.604**	**0.049**		1 Year Lag	11	0.397	0.179
2 Year Lag	9	-0.107	0.755		2 Year Lag	11	0.330	0.270
3 Year Lag	9	-0.123	0.736		3 Year Lag	11	0.311	0.301

Linear regression models were created to model the relationship of the larger storm surges and the indexed chronology (Figure 11). This result confirms that growth decreases following a hurricane occurrence and provides a reason to continue the path of determining the relationship.

3.3 Suppression Chronology Formation and Testing

Using a master chronology can be difficult when attempting to compare tree growth to climate parameters. To form that master chronology, first, a detrending curve is applied to the data to remove the growth trend. Then the individual series are normalized so that they fit a standard range of values to be compared to another dataset in the future, and finally are averaged together to produce one master chronology. These statistical data manipulation processes can transform the data in a way that removes a climate signal that was once present in the data.

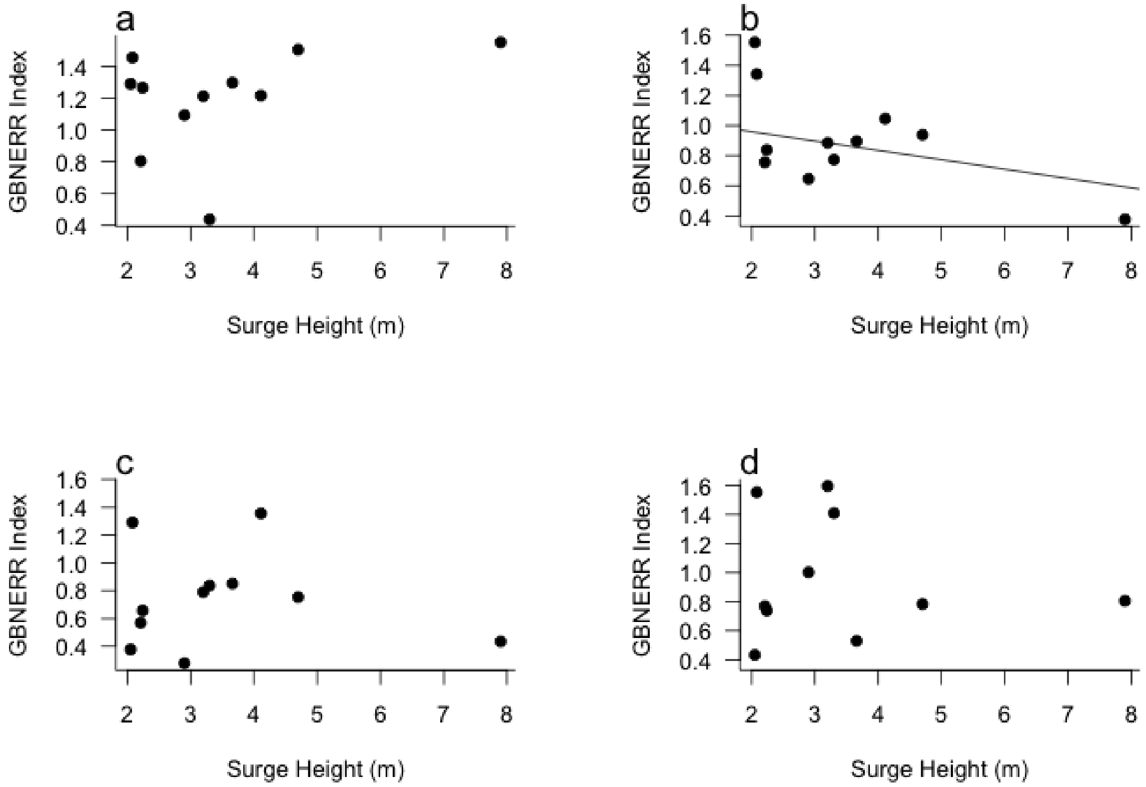


Figure 11: Linear regression models created to model the relationship between hurricane storm surge and indexed tree-ring width. (a) the same year of growth as hurricane occurrence, (b) the hurricane occurrence with the following year of growth, (c) growth two years after, and (d) growth three years after. Only (b) is significant and contains a line of best fit for comparison.

Other statistical processes can be used to assess tree-ring data that do not unnecessarily manipulate the data. For this study, the computer program JOLTS was used to identify when canopy disturbances occurred in this site (Holmes 1999). JOLTS is commonly used in tree-fire studies for describing a release of growth in trees, however, it can also be used for suppressions of growth (Brose and Waldrop 2010; Lafon and Speer 2002). For this study, the best canopy disturbances were identified using a running mean of six years (four years before and two years after) on the raw ring width measurements on each individual tree core. When a 15% decrease in growth occurred, a suppression was marked in JOLTS. The final 'suppression chronology' contains two columns: one with the year of suppression and one with the percentage of trees showing a suppression in that year. This suppression chronology was compared to hurricane parameters using the computer program EVENT that uses superposed epoch analysis (SEA) to describe a relationship (Holmes et al. 1986).

SEA is a statistical method used to resolve noise problems in data (Gannon 2012). Monte Carlo simulations are used to form a large number of expected values simulated from the observed values. The suppression chronology used in this study is analyzed against (a) the top ten hurricane occurrences at the site based on the combined lowest 10 rankings in Tables 2 and 3 (n = 10), (b) the higher half of surges in Table 2 (those above the mean) (n = 6), and (c) the larger half of wind speeds in Table 3 (n = 10). The higher half of storm surge and wind event records will be denoted as “high storm surge events” and “high wind events” respectively.

Figures 12, 13, and 14 show the results for the SEA analysis from this study for total, latewood, and earlywood ring widths, respectively. These variables are plotted against the departures from the mean Monte Carlo simulation results. This graphical method of mapping significance has been used in dendrochronological studies (Harley et al. 2011). The suppression chronologies created in this study were used for analysis, but for ease of comparison, direction of growth is plotted. The vertical bars represent the likelihood of growth being suppressed as related to the mean growth (horizontal bar). If a bar extends above the mean, growth was suppressed for that year. If the bar extends below the mean, growth was released that year. The dotted lines are the 95th percentile confidence intervals; the solid lines beyond the dotted lines are the 99th percentile confidence intervals. The SEA used in this study includes analysis of three years before and after the year of hurricane occurrence.

For example, Figure 12a shows a small release in growth 3, 2, and 1 years before a year of hurricane occurrence, a suppression the year of, and 1 and 2 years after a hurricane occurrence, and finally a release in growth the third year after a hurricane occurrence. The only significant result in Figure 12a is the suppression of growth the year directly after a hurricane occurrence, depicted by the vertical bar that year extending below the mean and reaching the 95th and 99th percentile confidence bounds. A similar result is found in Figure 12b where only those hurricanes with high storm surges were compared against the suppression chronology. No significance is seen in Figure 12c, in which hurricanes with high wind speeds were compared against the suppression chronology.

Figures 13 and 14 show similar results for latewood and earlywood, respectively. Above average growth precedes the year of a hurricane with decreases in growth the year of and the following year of a hurricane occurrence. Again, the only significant results are the decrease in growth one year after a hurricane occurrence, and these results are only significant in total (Figures 13a and 14a) and latewood (Figures 13b and 14b) ring width.

Though some *Pinus* species in the warmest areas of South Florida can grow all year long (75% of growth occurring February – August), the end of latewood growth for most southern pine species occurs in late September during the peak hurricane season (Harley et al. 2012b). Therefore, it is expected that the year of recorded storm surge would not affect that same year of tree-ring width. Additionally, it is expected that growth would be suppressed after the year of a hurricane occurrence and possibly be suppressed a number of years following the occurrence.

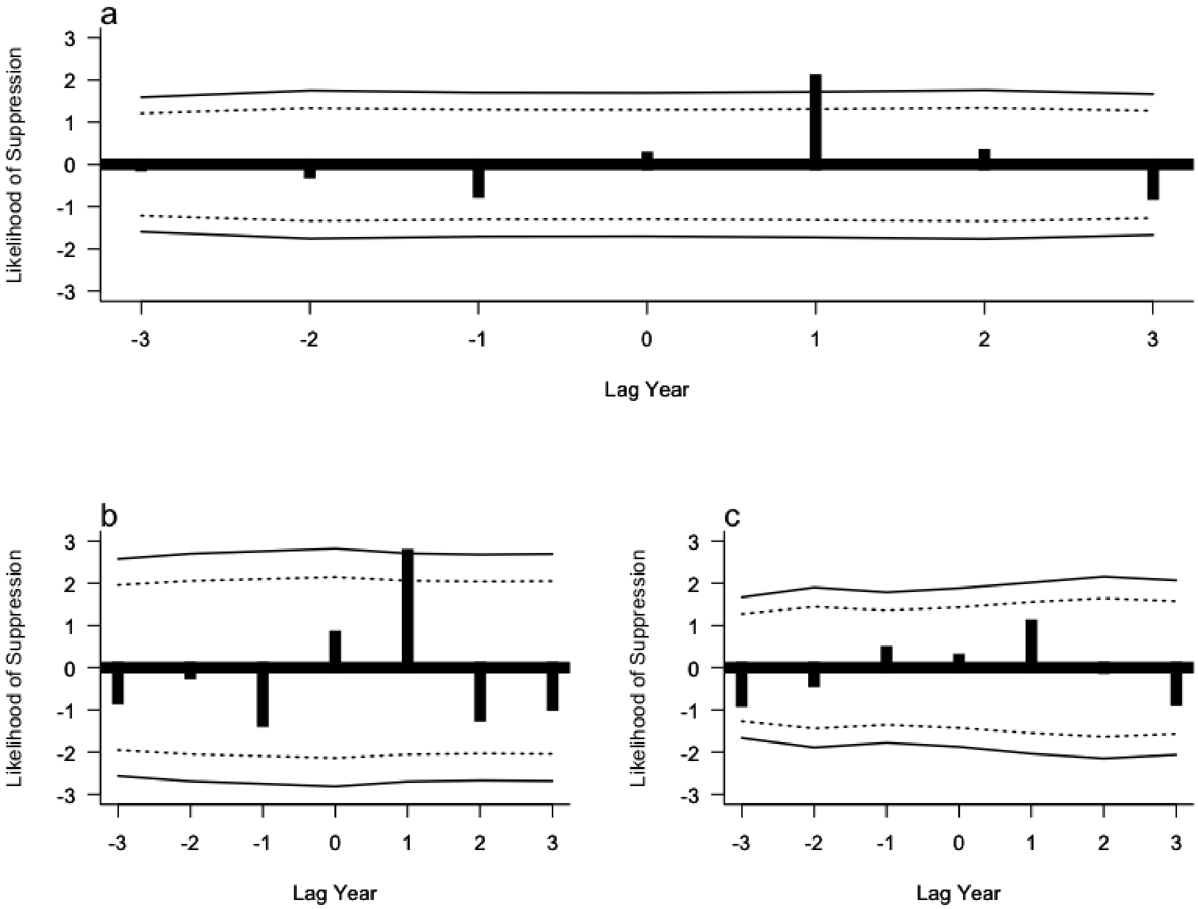


Figure 12: SEA of total tree ring width suppressions versus (a) top 10 ranked hurricane occurrences used in this study, (b) storm surge records above the mean, and (c) wind records above the mean. The vertical bars represent a decrease (below the mean) or increase (above the mean) in the likelihood of suppressed growth that year. The dotted and solid black lines represent the 95th and 99th percentile confidence bounds respectively.

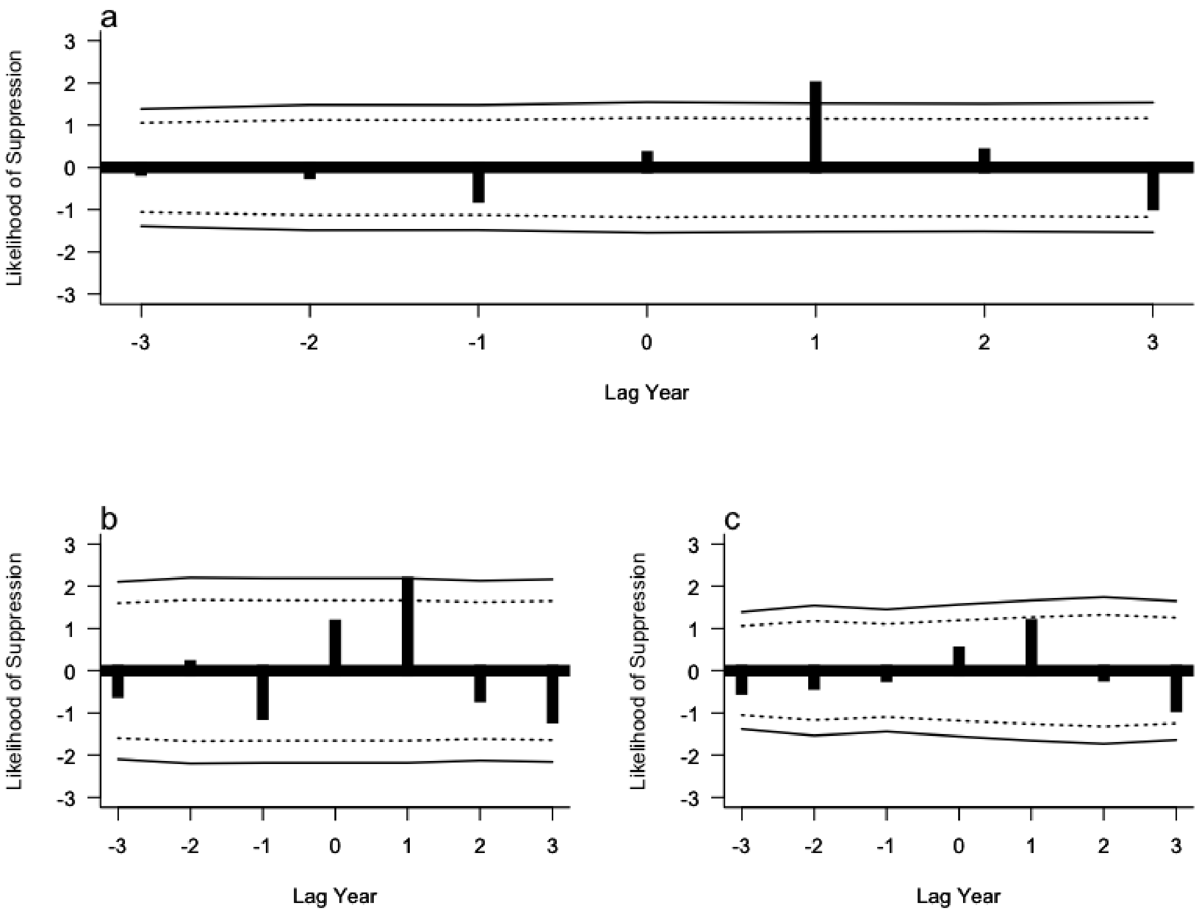


Figure 13: SEA of latewood tree ring width suppressions versus (a) top 10 ranked hurricane occurrences used in this study, (b) storm surge records above the mean, and (c) wind records above the mean. The vertical bars represent a decrease (below the mean) or increase (above the mean) in the likelihood of suppressed growth that year. The dotted and solid black lines represent the 95th and 99th percentile confidence bounds respectively.

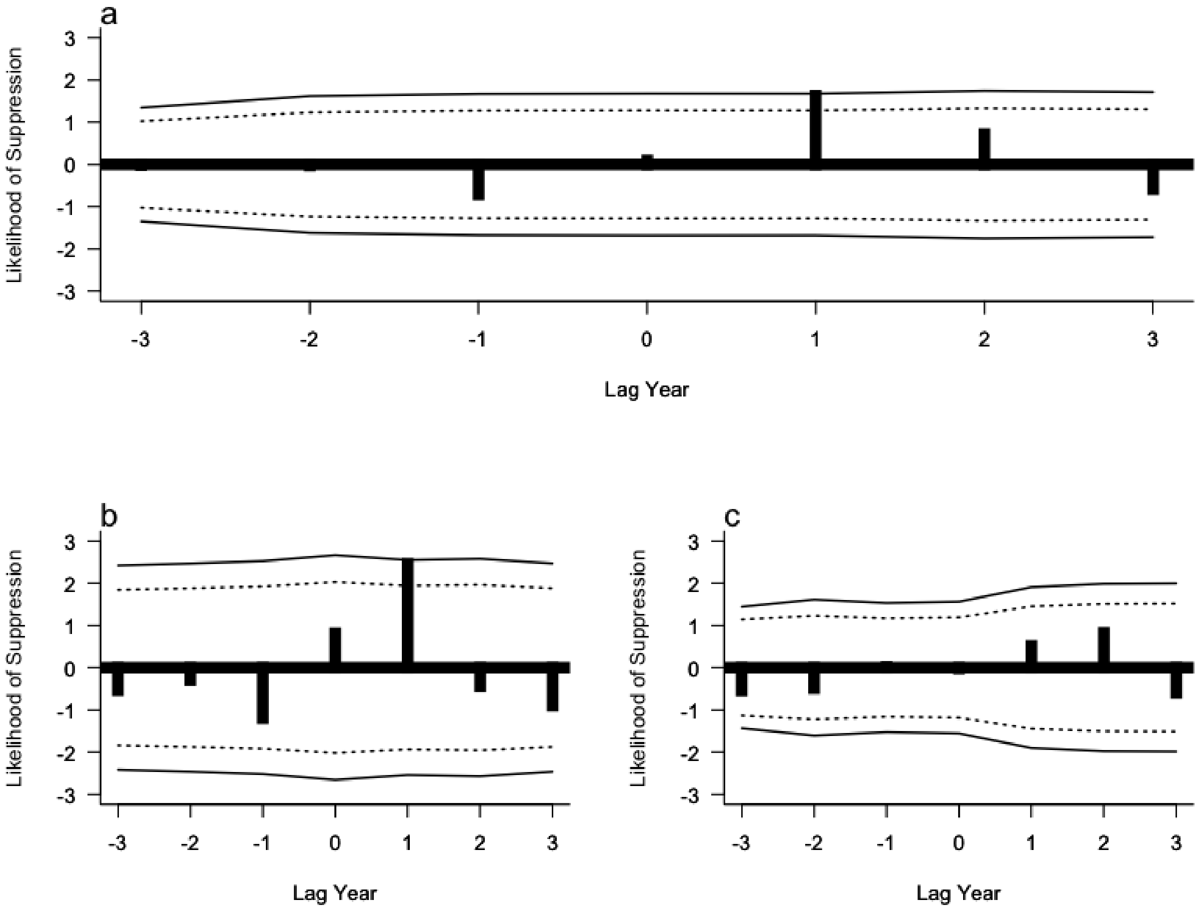


Figure 14: SEA of earlywood tree ring width suppressions versus (a) top 10 ranked hurricane occurrences used in this study, (b) storm surge records above the mean, and (c) wind records above the mean. The vertical bars represent a decrease (below the mean) or increase (above the mean) in the likelihood of suppressed growth that year. The dotted and solid black lines represent the 95th and 99th percentile confidence bounds respectively.

3.4 Testing for Climate Relationships with Tree Growth

The final objective of this study is to determine if any relationship to annual climate can be determined with the tree-ring dataset used in this study. PDSI was used for analysis in this study because it is commonly used for paleoclimate analysis and because it takes into account precipitation, evapotranspiration, and soil moisture conditions (Alley 1984; Meko et al. 1993; Palmer 1965; Stockton and Meko 1975). Table 5 contains the results for Pearson's r Coefficient analysis for the suppression chronology developed for this study and monthly PDSI values for the NCDC Climatic Division 10 for Mississippi.

Total ring width (TRW), earlywood ring width (ERW), and latewood ring width (LRW) suppression chronologies were analyzed against average annual PDSI, growing season months (March – October) PDSI, earlywood season months PDSI (March – June), and latewood season months PDSI (July – October). Those tests significant at ($p \leq 0.05$) are in bold. All relationships are negative, meaning that suppressions of growth decrease when PDSI increases, or is in a positive phase. This means that growth decreases during dry periods and increases during wet periods. TRW is significant only with respect to latewood season PDSI ($p = 0.043$) in any test, and it is suggestive ($p \leq 0.1$) with respect to averaged full growing season PDSI ($p = 0.099$). LRW is not significant with respect to any test, but is suggestive with latewood season averaged PDSI ($p = 0.093$). Interestingly, ERW is significant in every test, with the highest correlation with full growing season PDSI ($r = –0.225$).

Table 5: Results for Pearson's Correlation Coefficient (*r)* for tree-ring width suppression chronologies and PDSI. Significant results are in bold.

Test	df	*r*	*p*-value
Total Ring Width (TRW) and Annual PDSI	104	–0.154	0.115
Earlywood Ring Width (ERW) and Annual PDSI	**104**	**–0.217**	**0.025**
Latewood Ring Width (LRW) and Annual PDSI	104	–0.092	0.350
TRW and Full Growing Season PDSI	104	–0.161	0.099
ERW and Full Growing Season PDSI	**104**	**–0.225**	**0.020**
LRW and Full Growing Season PDSI	104	–0.101	0.300
TRW and Earlywood Season PDSI	104	–0.098	0.318
ERW and Earlywood Season PDSI	**104**	**–0.208**	**0.033**
LRW and Earlywood Season PDSI	104	-0.022	0.826
TRW and Latewood Season PDSI	**104**	**-0.197**	**0.043**
ERW and Latewood Season PDSI	**104**	**-0.206**	**0.035**
LRW and Latewood Season PDSI	104	-0.164	0.093

In summary, visual assessment of the indexed chronology determined that tree growth decreases following major hurricane occurrences, following large storm surges (those above the mean for GBNERR during 1909 – 2014), and following large wind events (those above the mean). Pearson's *r* and linear regression models show that growth does decrease significantly the year following storm surge occurrences using an indexed chronology of total ring width. Raw ring widths were used to form a suppression chronology that was compared to top 10 ranked storms used in this study, large storm surges, and large wind events. Significance was found for all of those variables for both total and latewood ring widths, but not for earlywood ring width. Finally, the suppression chronologies were compared to PDSI in which LRW was not significant in any test, TRW was significant only with latewood season PDSI, and ERW was significant in all PDSI tests.

4. CONCLUSIONS

The goal of dendrotempestology is two-fold: (1) to explain any ecoclimatological relationship between tree growth and hurricane occurrences and, if that is successful, (2) attempt to reconstruct hurricane occurrences before the current known record using trees older than the record. This study analyzes part one in which the viability of coatal trees is assessed for climate relationships. Trees in the southeastern United States receive plenty of rain and warm temperatures and because of this lack of limiting factors (i.e., stressors), the trees are not sensitive to climate. This study shows that extreme coastal locations closest to the ocean contain trees with sufficient stressors that cause the trees to be sensitive to climate. This represents another step toward reconstructing climate using Gulf of Mexico coastal trees.

Few studies been completed in this effort to explain the effects of hurricanes on trees. Some studies attempt to find this relationship using stable isotopes and tropical cyclone rainfall at the inland location of Valdosta, Georgia (Miller et al. 2006; Nelson 2008). Studies have explored the effects of hurricanes on tree growth, with some showing a decrease in tree growth from crown damage and defoliation (Doyle and Gorham 1994), while others show an increase in tree growth due to lack of competition from damaged and downed trees (Rodgers III et al. 2006). The combination of storm surge and high winds, which are greatest on the seaward edge, are detrimental to the growth of a coastal tree. However, these detriments do not cause large mortalities because the trees are specially adapted to hurricane characteristics. Speculations for these adaptations include densely-packed rings for a stronger stem, adaptations in root spread to reach freshwater, and damaging fire suppression from lack of leaf accumulation.

This study was largely compared to the early study of Rodgers III et al. (2006), which was in close proximity, throughout the research process. That study found using an indexed chronology showed an increase in growth for Weeks Bay, Alabama pine trees. Their explanation for an increase in growth was that hurricanes cause mortality in the stand and those trees that survived took advantage of the lack of competition for resources. They also found that using only an indexed chronology was not an effective way of analyzing this relationship because there was no significance in the result. It is possible that the statistical manipulations involved with creating a master index chronology mask or remove any signal from hurricane disturbances.

For this study, only a one-year lag saw significance with the indexed chronology and storm surge records only. This study found a different result seen in Rodgers III et al. (2006) which found a slight increase following a hurricane occurrence. Another issue may lie within the two different tree stands themselves. The trees may actually be responding differently to hurricane disturbance. In Weeks Bay, high mortality may follow a hurricane occurrence, and thus trees may increase in growth following a hurricane, whereas in Grand Bay, the tree stand may be adapted to withstand hurricanes, and instead of dying, they survive and must grow less in the stem in order to repair crown damage. A final issue may lie within the field methods used in the two studies. This study uses only trees close to the coast (within 2 km). Possibly, Rodgers III et al. (2006) study used trees further inland that do not respond the same to hurricanes.

A suppression chronology (percentage of trees suppressed per year) was formed in which raw ring widths were used to identify suppressions in individual trees. This method is commonly used in dendrochronology to detect disturbance regimes in a tree stand. It is often used in fire-tree reconstructions in which releases of growth follow the destruction of a stand-wide forest fire. A suppression chronology is favorable in disturbance studies because it uses raw ring widths from each individual tree for analysis so that tree growth is not detrended, averaged, or standardized. The results from the suppression chronology support the results from the master index chronology suggesting that the master index chronology in this study was not influenced by detrending and normalization. Multiple statistical methods are desirable for assessing the true nature of a physical relationship. Studies that rely on a single statistical test do not have the robust assessment and their results may contain false positives.

Suppressions were seen to be significant with respect to TRW and LRW in the year following a hurricane occurrence, large storm surge, or high wind event. However, ERW was not significant. This coincides with the idea that trees are damaged by hurricanes, but are adapted enough to survive through the disturbance and thus must repair and concentrate growth on the crown rather than growth at the stem. Simply from this analysis, it does not make sense that TRW and LRW only are suppressed and not ERW because ERW the following year is the first growth to occur after a hurricane, thus it should be significantly suppressed as well.

LRW decreases during the year of hurricane occurrence. This makes sense because peak hurricane season occurs before the end of the growing season. Therefore, I believe that crown-concentrated growth and repair occurs before the growing season ends, thus causing a decrease in growth to the stem. ERW does experience its largest decrease in growth the year following a hurricane. This may be an artifact of individual growth in trees. Though growth decreases stand-wide, some trees may be able to recover more quickly than others due to specific variables on individual trees.

Though ERW was not significant ($p \leq 0.05$) with hurricane variables, ERW was significant with every PDSI significance test. This means that when a tree experiences drought, it grows less in the earlywood season of growth. This may explain that for the trees closest to the coast, drought affects how well trees are able to begin growth the following year. For a physical explanation, this makes sense because it is likely that the trees closest to the coast have a shallow freshwater table and access to freshwater is dependent on a year-by-year basis. If the shallow water table is not replenished the year before, then water availability is heavily affected because the availability is already low.

For explanations of how a hurricanes affects growth for multiple years, the three years of tree growth before and after a hurricane occurrence were explored. The only significant result was with one year following a hurricane, but it is useful to explore other results and attempt to find physical reasons for growth patterns. TRW and LRW experienced increases in growth for all three years prior to a hurricane occurrence. This may mean that before a hurricane occurrence (and after the previous hurricane occurrence), stem growth is on a steady increase. This may mean that the tree is slowly transitioning from crown-repair growth to full stem growth.

TRW and LRW also experience a decrease during the year of hurricane occurrence and the two years after a hurricane occurrence followed by an increase in growth three and four years after a hurricane occurrence. This coincides with previous research stating that trees need three to seven years to recover a crown-stem balance in growth following a hurricane (Doyle and Gorham 1994). This could be true for this study site, or possibly because hurricanes are so frequent in the study site trees never reach a full balance in growth and are in constant repair mode. This may be detrimental to the trees as a larger-than-normal hurricane may destroy the weakest trees. This may explain why very few trees are present in the stand older than 80 years and why trees closest to the coast grow at nearly half the rate of trees inland (see Figure 5)

The suppression chronology showed that fewer suppressions were found in the early part of the record (prior to 1960) than the later part. This is in part an artifact of the data used. Not all trees began growth at the exact same time. However, percentage of suppressions also decreased in the early part of the record. This is likely due to the fact that most of the trees used in this study were much smaller trees during that time period. Small trees are much less affected than large trees during a high wind because the small trees are protected by the large trees (Curtis 1942; Doyle et al. 1995). The results of this study support that previous research.

4.1 Summary

Many of the results of this study were compared to Rodgers III et al. (2006). Showing different results for the hurricane-tree growth relationship than another study only strengthens the need to further the research on this topic and produce better results for the field. In the future, it would be useful to compare the results of this study to other areas along the hurricane-affected Gulf of Mexico coast using pine trees nearest to the coast in areas such as Weeks Bay NERR, Apalachicola NERR, and Eglin Airforce Base. This research may also be applied to other species such as cypress and oaks in South Louisiana.

This study provides a new stressor to the arsenal for dendroclimatology. This study shows that growth in trees nearest to the coast is sensitive to climate. If this is true for other trees nearest to the coast that are much older than those trees in GBNERR, reconstructions for precipitation, drought, and climate teleconnections such as ENSO may be available in the tree-ring record. This opens up a whole new area previously unused for dendrochronological applications. Future studies could explore this relationship with respect to water resources in the Gulf Coastal Plain of the United States.

Age-structure studies may also be useful for past tree disturbances. As previously noted, many of the trees at GBNERR are less than 80 years old. This may be in part due to human activity at GBNERR (e.g. logging and turpentine industries), but different age classes may be present at GBNERR that are formed by a disturbance regime. The combination of human, fire, and hurricane disturbances may affect recruitment and establishment of trees at GBNERR. For example, in this study it appears that many trees are recruited in the 1950s and 1960s. This could be caused by a lull in hurricane frequencies in the 20th century due to the Atlantic Multi-decadal Oscillation (AMO). Future studies could find different establishment rates of trees at GBNERR and compare those rates to other forested sites along the Gulf of Mexico coastline.

In conclusion, this research provides support to much of the previous research done with tree growth and mortality rates. This study shows that some coastal pine trees area adapted to hurricane variables, and instead of perishing during the hurricane, they repair themselves and grow significantly less in the stem the following year. The intellectual merits of this study include (1) the use of new statistical methods for disturbance ecology (2) the discovery of the relationship between hurricanes and tree growth, and (3) an exploration of the resiliency of trees to hurricane variables. The broader impacts of this study include (1) a step forward in potentially increasing the length of the record of hurricanes, thus increasing the confidence of future hurricane occurrences and keeping people out of harm’s way, (2) a description of the effects of climate during a documented rapid change in global climate, (3) recommendations for future knowledge gained from coastal forest disturbance ecology, and (4) an identification of the hurricane damage to trees useful for coastal wetland conservation.

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APPENDIX

These are the raw tree-ring width measurements used in this study placed into the Tucson (decadal) format for convenience in applications to commonly used tree-ring software programs, such as COFECHA, ARSTAN, and EVENT. The measurements were taken to 0.001 mm precision in the computer program WinDENDRO. Included are the total ring width (**TRW**), latewood ring width (**LRW**), and earlywood ring width (**ERW**) measurements. The series are listed with the site first (2GB, or GBNERR, second phase) and the tree number and core side second (2A, or second tree cored, first core taken). If the tree core is listed as ‘S’, then that core was taken from the southern side (180^{o} bearing) of that tree.

TRW

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2GB2A   1939  2759
2GB2A   1940  4763  3364  2865  2387  2442  4323  3786  4997  1530  1854
2GB2A   1950   409  1075  1963  2157  1559  2313  3096  2504  2237  2485
2GB2A   1960  2707  2521  1969  2279  3263  3446  1969   753  1252  3566
2GB2A   1970  2879  1928  1425  1761   547  1399  1423  2630  2614  2631
2GB2A   1980   292   660  3083  2598   373   751   950  2197   655   393
2GB2A   1990   472  1605   923   684  1000  1414  2119  1134  1648   222
2GB2A   2000   222   952  1591   939   774  1472   213   299   229   695
2GB2A   2010   295   212   265   212   127 -9999
2GB2S   1938  4329  3373
2GB2S   1940  5741  3509  2790  2421  2185  2843  3018  3925   838  1798
2GB2S   1950   230   533  1152  1588  1106  1565  2273  2103  1541  2468
2GB2S   1960  1798  2082  1324  1837  3629  3397  1520  1076  1178  2521
2GB2S   1970  1548  1380  1273  1408   329  1073  1180  1905  1955  2401
2GB2S   1980  1255  1404  3716  4255  1479  1645  1082  1778  1652  1739
2GB2S   1990  1308  2579  2825  1756  2093  1544  2833  1418  1905  1016
2GB2S   2000   487  1989  2474  2029  1985  2115   510   254   632   426
2GB2S   2010   166   363   693   806   612 -9999
2GB4A   1909  1476
2GB4A   1910   546  1390   371  1364  1836  1469  2031  2580  1449   669
2GB4A   1920  1561  1199  1199  2402  1665  1876  2171  1748  2298  1431
2GB4A   1930  2603  3068  2643  2817  3118  4134  4116  3018  3954  2982
2GB4A   1940  2956  2444  2026  2790  2646  3241     0   421  1258   917
2GB4A   1950   379   526   498   687   338   825   846   973   931  1206
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2GB4A   1960   974  1841   740  1814  1666  1265   465   719   656  1396
2GB4A   1970   656   656   423   274   244   306   382   761   677   908
2GB4A   1980   537   707  2070  2709  1185   625   169  1079   666  1333
2GB4A   1990  1142  1160  1499  1288  1584  1755  1333  1439  1248   457
2GB4A   2000     0   450   763  1057   635  1786   275   233   360   275
2GB4A   2010   264   379   507   451   600 -9999
2GB4B   1929  3011
2GB4B   1930  3888  4555  4812  4262  3535  4522  6244  5305  3954  5839
2GB4B   1940  4678  3605  3624  3049  4852  4471  3800   992  2239  2260
2GB4B   1950   951  1141  1122  1608   883  1155  1669  1682   903  1366
2GB4B   1960  1282  1517   927  1854  1685  1479   654   634   529  1634
2GB4B   1970   812   966   783   694   278   694   136   391  1902  1357
2GB4B   1980  1146   610  3279  3068  1374  1079   487   973  1142  1184
2GB4B   1990  1182  2854  3064  1935  1893  2020  1999  1220  1156   741
2GB4B   2000     0   610  1206   862   882  1384   116   126   422   327
2GB4B   2010   337   431   695   717  1027 -9999
2GB4S   1913  1236  2099  2211  2304  4090  1413   289
2GB4S   1920  1047   671   629  2137  1730  1542  1885  1397  1622  2644
2GB4S   1930  1947  3289  4773  3627  3085  3400  4528  4824  3301  6437
2GB4S   1940  4156  3394  3976  3059  4335  4187  4842  1354  1756  2518
2GB4S   1950  1654  1372  1453  1642  1073  1686  1959  1583  1181  1765
2GB4S   1960  1176  1832  1411  1944  2222  1841   868   910   867  2388
2GB4S   1970  1351  1406  1303  1283   696  1474  1889  1566  1206  1359
2GB4S   1980  1771  3129  5494  3489  1862  1566  1163  2328  2540  2751
2GB4S   1990  2091  3745  3321  2222  2257  1806  2058  1029  1818  1029
2GB4S   2000    48   804  1142  1142   930  1985   239   147   476   463
2GB4S   2010   346   307   821   569   908 -9999
2GB9A   1966  1016  5744  6221 11195
2GB9A   1970  8834  5629  8233  9249  5222  5604  4562  5454  5275  5380
2GB9A   1980  3314  3632  4249  5246  2159  1521  2524  4064  1055  2516
2GB9A   1990  6229  5384  6970  6059  8481  3063  1133  2655  3235  1176
2GB9A   2000     0  2210  4229  3575  3642  3040   514   844  1516  1470
2GB9A   2010  1157  1665  3767  2601  2241 -9999
2GB9B   1962  7004  5887  6510  7763  6922  2493  3811  5447
2GB9B   1970  5094  3780  4868  4104  2614  3883  3229  3376  3168  2980
2GB9B   1980  2070  2258  3903  5323  2537  2070  1560  1987   800     0
2GB9B   1990  1117  1967  3797  4342  3383  3655  2310  2071  1782  1116
2GB9B   2000   336  2058  3171  1437   888  1386   317   349   868   465
2GB9B   2010   773  1002   875  1685  1837 -9999
2GB11A  1949  4114
2GB11A  1950  2099  3425  3827  3593  3408  4312  4976  3762  3537  5032
2GB11A  1960  3058  2777  1852  1858  2869  3056  2124  1385  1735  4058
2GB11A  1970  2441  2023  1390  1526   472   473   413   831  1061  1123
2GB11A  1980   786   445  1184  2507  1196  1199   985  1451   177  2194
2GB11A  1990  1866  1225  2016  2371  2543  2525  2297  1518  1244  1645
2GB11A  2000   653   714  1346  1578  1413  2518   434   148   338   212
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2GB11A  2010   159   307   487   444   609 -9999
2GB11B  1949  4446
2GB11B  1950  2976  3364  3301  4640  3573  5224  4725  4807  4472  4979
2GB11B  1960  3341  3678  2783  2669  3893  5003  2940  2052  1742  3205
2GB11B  1970  2211  1481  1415  1285   358   819   694   910   973  1142
2GB11B  1980   550   931  1523  3587  1407  1206   592  1541     0  1803
2GB11B  1990  2644  1680  1796  2115  1460  1037  1184   624   877   519
2GB11B  2000   211   613   889   720   931  1016     0   180   381   159
2GB11B  2010    85   337   380   391   688 -9999
2GB13A  1923  2585  1222  1529  2385  2737  3044  2744
2GB13A  1930  2049  3221  3062  2455  1651  1835  1379  1568  1259  1322
2GB13A  1940  1552   775  1301  1891  3036  2736  2878  2596  1545  1290
2GB13A  1950   148   254   635  1395   803  1839  2686  2328  1227  1523
2GB13A  1960   952  1079   614   930   952   634   761   211   296  1651
2GB13A  1970  1079   571   486   408   533   958   791  1479  1129  1690
2GB13A  1980  1198  1527  2442  2620   508   805   448   564   383   770
2GB13A  1990   455  2135  1198  1563  1499  2048  2997  2502  1596   441
2GB13A  2000   176   768  1431  1929  1299  2270   468   220   458   748
2GB13A  2010   541   639  1117   969   920 -9999
2GB13B  1927  3101  4211  3812
2GB13B  1930  3541  2256  2768  3220  2966  2220  2444  1973  1839  1709
2GB13B  1940  1621  1642   695  1014  1374  3238  2603  3238  1967   889
2GB13B  1950   508   635   887  2604  1381  2196  1777   700   401   783
2GB13B  1960   747  1106   467   656   983   606   419   222     0   758
2GB13B  1970   389   305   275   273   210   558   379  1309  1243   798
2GB13B  1980   772   523  1684  3249  1246   611   444   401   222   494
2GB13B  1990   588  1472  1746  1256   896   845   856  1202  1089   507
2GB13B  2000   112   687   929   850   745  1669   284   158   656   525
2GB13B  2010   376   595   735   419   555 -9999
2GB15A  1941  1566  1648   663  2204  1947  2431  2997  1821  1529
2GB15A  1950   870  1264   914  1110  1581  2581  2681  2178  1879  2142
2GB15A  1960   779   950   802   866  1037  1831   995   719   635  1924
2GB15A  1970     0     0   112   119   148   613   550   910  1205  1999
2GB15A  1980  1624  1009  2663  2294  1531  1382   991   973   540   799
2GB15A  1990   993  1540  1482  1027   930   867  1248  2281  1700   909
2GB15A  2000   222  1307  1769  1217  1343  1263     0   212   294   434
2GB15A  2010   221   422   886   528   740 -9999
2GB15S  1930  1278  1205  1914  1287   654  1146   907   871   691  2211
2GB15S  1940  2228  1668  1435   655  1971  1339  2086  2236  1392   969
2GB15S  1950   632  1350  1205  1562  1014  1503  2349  1820  1926  1820
2GB15S  1960   825  1141   592   972  1069  2120  1663  1410  1199  1934
2GB15S  1970     0     0   146    90   215   454   719  1397  1651  1904
2GB15S  1980  1630  1630  2620  2760  1666  1459   740   804   444   971
2GB15S  1990   801  1434   865   548   591  1479  1141   909  1206   510
2GB15S  2000   316  1609  1947  1228  1482  1546     0   275   273   462
2GB15S  2010   231   441   628   317   712 -9999
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2GB16A 1938  6448  6800
2GB16A 1940  6293  5486  5513  6718 10103  9545  8550  7425  4780  5306
2GB16A 1950  4708  3554  2743  3921  3326  6292  6947  5164  4208  5569
2GB16A 1960  2324  3538  2633  2368  2525  2986  1439  1058  1079  2324
2GB16A 1970  1121   846  1163  1375   360  1906   953  1254  1002  1303
2GB16A 1980   616  1046  1609  1446   484   683   449   801   691  1286
2GB16A 1990   634  1205   804   675   358   589   378   484   527   255
2GB16A 2000   263  1591  1154  1162   801  1279   317    49   642   190
2GB16A 2010   337   381   381   386   328 -9999
2GB16B 1940  4592  4529  4662  6037  8633  9163  9182  8006  6286  5543
2GB16B 1950  5178  3703  3349  3167  3013  4198  5656  4630  3470  4947
2GB16B 1960  2278  2892  2001  2540  3093  3200  1659   731   859  1819
2GB16B 1970  1417  1100   865  1009   589  1819  1085  1193  1212  1372
2GB16B 1980   950   702  1705  2248   641  1926   968  1345   850   865
2GB16B 1990   391  1519  1055  1402   998   724   581   933  1248   677
2GB16B 2000   845  1095  1327  1162   867   867   311   133   620   394
2GB16B 2010   423   319   464   375   400 -9999
2GB17A 1943  7111  9011  5644  5148  4692  4508  4653
2GB17A 1950  4292  3049  2479  2986  2703  4508  5354  3206  3026  3685
2GB17A 1960  1857  2999  2220  3005  3617  2548  1432  1327  1450  2572
2GB17A 1970  1146   813   709   664   475   824   691   981   934   977
2GB17A 1980   807   323  1297  1539   499   728   333   835   420   918
2GB17A 1990   665   949   780  1099   866  1034   758   588   793   556
2GB17A 2000    63   728   646  1084  1305   687    93   319   560   298
2GB17A 2010   147   131   321   254   365 -9999
2GB17S 1941   367  6005  7293 11534  8665  8441  7733  3468  3826
2GB17S 1950  2708  2522  2540  2850  2355  2910  3708  2721  2676  3430
2GB17S 1960  1890  2561  1285  1852  1917  1371   949   991   947  1496
2GB17S 1970   780   728   708   889   762   847   889  1311  1163  1784
2GB17S 1980   982   487  1376  1481   296  1333   479   622   479   402
2GB17S 1990   264   167   423   798   536  1143   868   698   744   483
2GB17S 2000     0   995   698   783  1101  1188   117   264   419   268
2GB17S 2010   233   231   222   348   464 -9999
2GB18S 1939  5651
2GB18S 1940  4281  3821  3613  3720  4885  4200  4091  3697  3061  1732
2GB18S 1950  1222  1988  1883  2193  1482  1723  2913  2664  2434  2767
2GB18S 1960  1647  1373   910  1375  1396  2151  1244  1066   814  1988
2GB18S 1970  1692  1270  1248  1690   739  1161   865  1624  1179  1198
2GB18S 1980   862   856  1253   691  1372  1077  1224  1349     0  1031
2GB18S 1990   755  2265  1096  1671  1185   635   741   635   761   888
2GB18S 2000   195   820   804   804   931   695   341   378   431   328
2GB18S 2010   265   275   360   211   317 -9999
2GB20A 1972  3426  8429  4819  8342  7732  8997  7196  8455
2GB20A 1980  3006  2708  4402  4967  3106  4018  5055  6259  1113  4043
2GB20A 1990  5224  6451  5433  5319  4209  4219  2515  2515  3966  2772
2GB20A 2000   938  2580  3109  2877  3839  4241  1756  2137  2435  1645
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2GB20B  1970  4940  7909 10175 11305  4456  7407  7955  9679  8041  9271
2GB20B  1980  4025  3080  6944  7487  4014  4697  5654  7247  2348  5936
2GB20B  1990  6183  7805  8624  6648  6198  5689  5001  4914  5178  3260
2GB20B  2000  1269  2705  2980  2539  3259  4154  2500  2426  2584  2336
2GB20B  2010  1342  2439  2293  1741  1405 -9999
2GB21A  1960  4560  6969  7205 10026  8906  8984  5230  4501  4642  8538
2GB21A  1970  4836  2806  3746  3067   931  1629  1206  2771  2307  2324
2GB21A  1980  1880  1415  3085  2726  1351   569   539   730   295   561
2GB21A  1990   807  2156  1209  1319  1759  2722  1926  1989  2276  1245
2GB21A  2000   677  1925  3343  3323  2561  1671   328   645   847   550
2GB21A  2010   317   719  1608   952  1036 -9999
2GB21B  1961  8193  7786  8244  7336  8122  5850  5139  5175  7307
2GB21B  1970  2819  2798  3252  3092  1494  2524  1870  2556  2091  2169
2GB21B  1980  2150  2009  3101  2424  1456   761   614  1014     0   635
2GB21B  1990  1919  1413  1204  1543  1755  1543  2008  1776  1351  1060
2GB21B  2000   165  2635  3647  2282  1564  1199   379   700   755   587
2GB21B  2010   323   825  1523  1029  1278 -9999
2GB22A  1971  4955  7573  5697  2212  4984  4634  6847  4408  6134
2GB22A  1980  3916  4133  4874  4859   621  1225  1690  2506   666  1016
2GB22A  1990  2815  5153  4083  3470  3254  2032   656  1101  1249   709
2GB22A  2000     0  1069  1630  1884  2158  1777     0    63   360   947
2GB22A  2010   138   243   527   286   452 -9999
2GB22B  1964  5197  4493  6560  2693  4454  8614
2GB22B  1970  4652  5012  6521  4825  2356  3840  3507  7489  3608  3456
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2GB22B  1990  1338  2626  2020  1946  1821  1543   874  2016  2844  1805
2GB22B  2000   263  1340  1108  1760  1034   871     0   414   528   603
2GB22B  2010   367   329   695   676   602 -9999
2GB23B  1964  9557  8253  6870  6958  7558 10286
2GB23B  1970  7721  5313  6948  5846  3071  5673  5352  5633  4264  4692
2GB23B  1980  2902  3367  8316  5904   910  3640  3704  2688   593  1736
2GB23B  1990  2624  4422  3531  2962  2622  4398  3270  2294  2223  1299
2GB23B  2000  1003  2534  3344  2468  1837  1500   359   909  1372  1164
2GB23B  2010   696   656  1747  1204  1459 -9999
2GB23S  1962  4069  3877  8041  8630  6683  6586  6822  9947
2GB23S  1970  7223  5385  5241  4254  2912  5681  4118  3637  2982  4664
2GB23S  1980  3061  3041  3617  2390   651  2607  1954  1902   461  1899
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2GB23S  2000  1320  2409  2567  2276  1615  1968   886  1199  2228  1322
2GB23S  2010  1085   980  1666  1332  1049 -9999
2GB24B  1968  7151  7302
2GB24B  1970  9902  1498  4245 11288  5358  3808 10931  7257  7575  5170
2GB24B  1980  5848  3932  6125  7718  6282  2773  2872  4603   593  2530
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2GB24S  1972  5870 13099  7232  3641  9829  7000  9029  4682
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2GB24S  1990  2562  5734  4799  5248  3273  3211  2711  2144  2214  1434
2GB24S  2000  1524  2358  2877  1369  1583  1202   441   675  1267   825
2GB24S  2010   454   540   689   532   663 -9999
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2GB25A  1970  2600  4100  5965  4825  1707  9033  6578  8413  7627  8360
2GB25A  1980  8458  6681  9751  8326  2443  5105  4825  5270  1063  4141
2GB25A  1990  4442  5250  5525  4985  4546  4034  4109  2762  3170  1661
2GB25A  2000  1893  2850  3136  2524  2185  2273   688   930  1777  1627
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2GB25B  1970  3604  4605  5754  6681  3148  6008  5480  7258  5334  4626
2GB25B  1980  4608  4774  6084  5967  1503  4741  3682  4169   850  2520
2GB25B  1990  3357  5982  5438  5018  2653  3391  4033  2635  3429  2007
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2GB25B  2010  1053  1438  1100   951   660 -9999
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2GB2B   1970  1877  1444   773  1707   231   884   632  1283  1324  1434
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2GB2B   1990   377  2139  1405   670  1109  1272  1124   571   463   392
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2GB2B   2010    51    67   316   282    94 -9999
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2GB2S   1940  3328  1282  1056  1336  1061  1328  1562  2131   607  1003
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2GB2S   2000   169  1354  1311  1036  1183  1163   235   108   212   299
2GB2S   2010     0   130   274   341   193 -9999
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2GB4A   1920   714   590   315   927   569   232   834   831  1096   610
2GB4A   1930  1439  1650   803  1343  1517  1961  1921  1499  2019  1396
2GB4A   1940  1225  1348   612  1247  1460  1894     0   169   899   337
2GB4A   1950   147   232   159     1   127   550   465   486   317   507
2GB4A   1960   296   878   296  1055   591   422   148   360   169   697
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2GB4S   1960   525   927   632   993  1100  1016   377   444   338  1241
2GB4S   1970   739   524   399   610   253   755   682   756   783   783
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2GB9A   1966   808  3362  2122  3842
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2GB9B   1962   317  3678  1161  2651  3012  1651  2351  2472
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2GB9B   2000   210  1638  1691   613   381   582    95   275   550   169
2GB9B   2010   402     0   521  1073   887 -9999
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2GB11A  1980   141   202   561  1232   378   694   168   429    72  1345
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2GB11A  2000   316   357   715   694   569   931   116    32   117    95
2GB11A  2010    74   138   117   159   179 -9999
2GB11B  1949  2026
2GB11B  1950  1372   931  1573  2149  2016  3136  2372  2568  2134  2816
2GB11B  1960  1525  1661  1280  1019  1680  2903  1180   995   651  1718
2GB11B  1970   948   550   317   527    84   462   421   444   338   566
2GB11B  1980   127   402   804  2002   370   719    63   760     0   964
2GB11B  1990  1511   406   877  1057   402   275   275   139   344   149
2GB11B  2000    42   296   359   254   402   466     0    32    74    22
2GB11B  2010    30   147    64   159   170 -9999
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2GB13A  1930  1138  1631  1520   550   804   729   501   836   608   881
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2GB13A  1940   420   419   734   840  1813  1600  1155  1076   466   444
2GB13A  1950   127   148   381   655   423  1290  1354   635   381   656
2GB13A  1960   402   317   190   359   296   296   380   116   106   931
2GB13A  1970   539   211   127    94   125   333   312   396   564   985
2GB13A  1980   584   893  1152  1195   117   483   136   383   101   365
2GB13A  1990    59  1277   530   637   720   995  1938  1365   762   199
2GB13A  2000     0   394   809  1224   579  1383   149    90   183   445
2GB13A  2010   221   200   614   429   242 -9999
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2GB13S  1950   310   585   565  1009   646   825   699   165   165   373
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2GB13S  1970   147    63    90   143    97   455   352   559   604   581
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2GB13S  2010    10    73   296   243   265 -9999
2GB15A  1941   741   850   295  1054  1230  1153  1894   837   754
2GB15A  1950   479   598   499   482   991  1630  1627  1036   918  1277
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2GB15A  1990   476   675   529   356   274   275   740  1457   792   518
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2GB15A  2010   126    84   295   115   106 -9999
2GB15B  1941   582   815   356  1134  1066  1156  1072   714   484
2GB15B  1950   417   587   463   780   622  1639  1880  1104  1200  1363
2GB15B  1960   584   690   293   502   960  2192   924   727   285  1766
2GB15B  1970     0     0    84   169   338   444   338   804  1587  2793
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2GB15B  1990   316  1035  1354   677   677  1016  3936  3036  1672   624
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2GB15B  2010    21   222   444   116   158 -9999
2GB15S  1923    94   441   364  1790   400   389   756
2GB15S  1930   670   634   884   359   232   500   306   290   356  1069
2GB15S  1940  1014   845   781   380  1002   886   906   959   706   537
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2GB15S  2010     2   127   335   128   212 -9999
2GB16A  1938  1195  1344
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2GB16A  1980   144   583   623   754    52   449    71   472   335   843
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2GB16A  2000    96   906   392   366   359   440    80    30   242    85
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2GB16B  1940  1121  1038   978  2242  2039  2612  4210  3560  3143  3045
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2GB16B  1980   151   316   904  1193   126  1256   193   583   295   355
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2GB16B  2000   338   442   779   296   402   254   205    55   114   212
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2GB17S  1950  1116  1513   861  1467  1115  1666  2065  1181  1327  1641
2GB17S  1960   861  1070   463   800   568   569   380   232   253   758
2GB17S  1970   537   222   317   339   339   317   295   423   444  1025
2GB17S  1980   127   275   783   783    85  1101   182   402   141   289
2GB17S  1990    66    85   169   226   254   487   296   275   364     0
2GB17S  2000     0   571   190   360   402   491    63    68   106    78
2GB17S  2010   185    15   110   163   163 -9999
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2GB18S  1980   231   459   626   272   823   401   591   738     0   526
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2GB21A  1990   207  1120   542   858   963  1528   942  1026  1602   717
2GB21A  2000   233  1206  2179  2603  1757   825   159   212   360   169
2GB21A  2010   127   454   762   360   275 -9999
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2GB21B  1990   840   801   591  1014   761   719   782   909   676   279
2GB21B  2000   133  1370  2150  1231   655   544   162   360   422   333
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2GB22A  2000     0   635  1058  1143  1354   529     0    21   212   505
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2GB2S   1950   105   147   476   857   563   575   980   895   669  1066
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2GB4C   1913   583  1191  1510  1002  3133   748    83
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2GB4C   1930  1016  1453  2123  2488  1500  1478  2116  2285  1430  2026
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2GB4C   1950   995   800   948  1010   631   801   843   996   527   719
2GB4C   1960   651   906   779   951  1122   825   491   466   529  1147
2GB4C   1970   612   881   903   673   443   718  1206   809   423   576
2GB4C   1980   921   803  2493  2093  1143   811   677  1185  1270  1227
2GB4C   1990  1336  1650  2094  1206  1287  1071  1218   714   825   528
2GB4C   2000    21   388   656   508   444  1098   147   139   329   379
2GB4C   2010   240   202   484   401   718 -9999
2GB9A   1966   207  2382  4100  7353
2GB9A   1970  4467  2572  4074  4782  2653  2435  1598  1958  2722  1920
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2GB9A   1990  1499  2334  1920  1241  3162  1964   350   249  1210   231
2GB9A   2000     0   631  1094  1346  1242  1397   144   515   611   882
2GB9A   2010   316   717  1206   952  1738 -9999
2GB9S   1967  2006  5620  2576
2GB9S   1970  1918  3237  3640  1714  1650  1603  2231  2368  1031   234
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2GB9S   2000     0   973   766   760   889  1223     0   144   102   336
2GB9S   2010   383   274   911   677  1153 -9999
2GB11A  1949  2200
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2GB11A  1960  1557  1532  1116  1162  1603  1075  1094   734  1143  2252
2GB11A  1970  1043  1293  1079  1113   369   309   289   446   600   401
2GB11A  1980   645   243   623  1274   819   505   817  1022   106   849
2GB11A  1990   996   955   831  1301  1534  1641  1370  1159   822   864
2GB11A  2000   337   357   631   884   843  1587   317   116   222   116
2GB11A  2010    85   169   370   285   430 -9999
2GB11B  1949  2421
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2GB11B  1960  1816  2017  1503  1651  2213  2100  1760  1057  1091  1487
2GB11B  1970  1264   931  1099   759   274   357   273   465   634   577
2GB11B  1980   423   529   719  1586  1037   487   528   781     0   839
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2GB11B  2010    54   189   316   232   517 -9999
2GB13A  1923  2127  1008   854  1079  2207  2114  1688
2GB13A  1930   911  1589  1541  1905   846  1106   878   732   650   441
2GB13A  1940  1133   356   566  1050  1223  1137  1723  1519  1079   846
2GB13A  1950    21   106   254   740   380   550  1332  1693   846   867
2GB13A  1960   550   762   423   571   655   338   380    95   190   719
2GB13A  1970   540   359   359   314   408   625   479  1083   564   705
2GB13A  1980   615   635  1289  1425   391   322   311   181   282   405
2GB13A  1990   396   858   668   926   779  1054  1059  1137   835   241
2GB13A  2000   176   374   622   705   719   886   319   130   275   303
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2GB13A  2010   321   440   503   541   678 -9999
2GB13S  1920  1076   759   625  1378   693  1490  1333  2317  2253  1723
2GB13S  1930  1537  1869  1815  2229  1504  1239   983   917  1101  1037
2GB13S  1940  1562   564   876  1445  1676  1283  1323  1318   995  1019
2GB13S  1950   204   444   766  1614  1090   846  1069   391   350   373
2GB13S  1960   539   581   538   748   833   605   485   168   293   546
2GB13S  1970   294   167   126    99    52   289   310   642   625   706
2GB13S  1980   887   352   956  1247   564   188   230    55    62   506
2GB13S  1990   493   849   568   676   529   633   656   550   719   296
2GB13S  2000    51   317   783   593   698   390   148    64   371   254
2GB13S  2010   435   456   265   359   477 -9999
2GB15A  1941   825   798   368  1150   717  1278  1103   984   774
2GB15A  1950   391   666   416   629   590   951  1054  1142   961   865
2GB15A  1960   442   549   549   528   635   679   508   339   444  1014
2GB15A  1970     0     0    83    77   148   338   254   466   528   695
2GB15A  1980   970   399  1116  1230   827   454   722   580   353   310
2GB15A  1990   517   865   952   671   655   592   508   824   908   391
2GB15A  2000   138   484   675   587   692   674     0    85   231   275
2GB15A  2010    95   337   591   413   634 -9999
2GB15B  1941   831   606   294  1014   697   892  1199   525   505
2GB15B  1950   396   482   316   906   497   747  1149   674  1053   839
2GB15B  1960   480   669   503   481   919  1016   904   602   702  1093
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2GB15B  1980  1746   698   994  1522   971   801   736   608   484   737
2GB15B  1990   759   634   825   868   804  1164  1185  1577  1249   391
2GB15B  2000   339   760  1228   709  1235  1208   339   180   370   433
2GB15B  2010   339   402   603   666   886 -9999
2GB16B  1940  3471  3492  3684  3794  6594  6552  4971  4445  3143  2498
2GB16B  1950  2536  1644  1615  1770  1312  1859  2588  1877  1545  1480
2GB16B  1960  1196  1520  1243  1149  1588   969   893   422   563   888
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2GB16B  1990   314   717   524   883   686   579   461   601   762   529
2GB16B  2000   507   653   548   866   465   613   106    78   507   182
2GB16B  2010   275   177   254   298   315 -9999
2GB16A  1938  5253  5456
2GB16A  1940  5267  3509  3503  4168  5723  5693  4127  2792  2411  2226
2GB16A  1950  2625  1380  1717  1971  1600  2618  3305  2057  1989  2251
2GB16A  1960  1235  1675  1650  1337  1284   904   825   571   698  1648
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2GB16A  1980   472   463   985   692   432   234   378   329   356   443
2GB16A  1990   317   613   487   549   210   399   291   294   359   148
2GB16A  2000   167   684   762   796   443   839   237    19   400   106
2GB16A  2010   210   233   275   275   228 -9999
2GB17A  1943  3386  5352  3076  2958  2417  1716  2094
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2GB17A 2000   31  728  396  654  819  461   74  150  360  159
2GB17A 2010   78   96  235  155  215 -9999
2GB17S 1941  360 4276 2916 7405 5431 4625 2233 1744 1892
2GB17S 1950 1592 1009 1679 1383 1241 1244 1643 1540 1348 1789
2GB17S 1960 1029 1490  822 1052 1348  801  569  759  695  737
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2GB17S 2000    0  423  508  423  698  698   53  196  313  190
2GB17S 2010   48  216  112  185  301 -9999
2GB18S 1939 4995
2GB18S 1940 3291 3124 2384 2494 3094 1803 2426 1874 1831  908
2GB18S 1950  408 1057  889 1125  710  877 1625 1882 1439 1277
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2GB18S 1970 1079  804  846 1014  570  633  422  949  695  735
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2GB18S 2010  172  161  245  160  224 -9999
2GB20A 1972 1650 5815 1865 5324 3919 4720 4021 4418
2GB20A 1980 2053  824 1926 2367 1679 1256 2119 3615  148 1515
2GB20A 1990 2283 3024 2579 2850 1354 1835 1228  909 1501 1088
2GB20A 2000  200  994 1036  846 1036  961  275  931 1184 1202
2GB20A 2010  372  421  845  506  631 -9999
2GB20B 1970 2481 6264 5909 6956 2207 4008 3426 4787 3169 4623
2GB20B 1980 2445 1117 2011 2917 1498 1225 2204 3284  463 2068
2GB20B 1990 3203 3451 3993 2902 1575 1966 1827 1588 1822  888
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2GB20B 2010  636  665  799  629 1070 -9999
2GB21A 1960 4341 5773 3652 6015 5616 4004 3674 3182 2363 3540
2GB21A 1970 2795 1160 1651 1692  423  487  402 1015 1079 1078
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2GB21B 1961 7181 6918 5454 5645 4252 3865 2843 2819 3551
2GB21B 1970 1148 1023 1594 1746  757 1094  834 1215  920 1382
2GB21B 1980 1244  973 1224 1180  844  338  466  422    0  360
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2GB21B 2000   32 1265 1497 1051  909  655  216  340  333  254
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2GB22A 1971 1853 4292 2945 1182 1943 1929 3136 2307 3101
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2GB22A  2000     0   434   571   741   804  1248     0    42   148   442
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2GB22C  1965  2294  3656  3077  2308  5020
2GB22C  1970  2380  3571  3760  3039  1397  2243  2031  3364  2560  2487
2GB22C  1980  2330  1659  2079  2749   208   500   735  2108   134   567
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2GB22C  2000    42   487   783  1496  1118   973     0   128   148   335
2GB22C  2010    93    84   198   534   315 -9999
2GB23A  1963   220  5329  4509  3638  3515  4315  6043
2GB23A  1970  3759  2539  2646  2601  1775  2344  1862  3300  2618  2260
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2GB23A  2010   615   414   632   737   757 -9999
2GB23B  1964  6367  4802  3911  3109  4041  5143
2GB23B  1970  2750  2762  3084  3081  1683  2416  1798  2701  2217  1906
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2GB24B  1968  3523  4038
2GB24B  1970  6046   760  1647  5659  2821  2158  4971  3702  3702  2293
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2GB24S  1972  2206  9773  3708  1632  3723  2292  3330  2383
2GB24S  1980  1806  2565  1940  2913  2810   528  1032  2162   639   477
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2GB24S  2010   144   240   203   204   456 -9999
2GB25A  1968  6452  8095
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2GB25A  1980  4839  4207  4622  4101  1238  1678  2596  3075   406  1450
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2GB25B  2000   881  1218   951   938  1057   782   169   190   634   585
2GB25B  2010   538   613   592   592   487 -9999
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VITA

Clay Stephens Tucker is a seventh generation native of Baton Rouge, Louisiana. He received his bachelor’s degree from Louisiana State University in 2013. He has worked with a number of facilities on campus involving coastal research including a research assistantship at the Coastal Sustainability Studio, a teaching assistantship in the Department of Geography and Anthropology, and a graduate research assistantship for the South Central Climate Science Center. Clay has presented research at the Annual Meeting for the Association of American Geographers and the Annual Meeting for the Southeastern Division of the Association of American Geographers. He is a co-author on a published paper in the peer-reviewed journal PLOSOne.

His interests in coastal studies stem from growing up with his family and friends in South Louisiana. He will receive his Master’s Degree in December 2015 and plans to begin his Doctorate at LSU upon graduation.