Determining the Viability of Recent Storms as Modern Analogues for North-Central Gulf of Mexico Paleotempestology Through Sedimentary Analysis and Storm Surge Reconstruction

Joshua Caleb Bregy
University of Southern Mississippi

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DETERMINING THE VIABILITY OF RECENT STORMS AS MODERN
ANALOGUES FOR NORTH-CENTRAL GULF OF MEXICO
PALEOTEMPESTOLOGY THROUGH SEDIMENTARY
ANALYSIS AND STORM SURGE RECONSTRUCTION
by
Joshua Caleb Bregy

A Thesis
Submitted to the Graduate School and the Department of Marine Science at The University of Southern Mississippi in Partial Fulfillment of the Requirements for the Degree of Master of Science

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2016

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ABSTRACT

DETERMINING THE VIABILITY OF RECENT STORMS AS MODERN ANALOGUES FOR NORTH-CENTRAL GULF OF MEXICO PALEOTEMPESTOLOGY THROUGH SEDIMENTARY ANALYSIS AND STORM SURGE RECONSTRUCTION

by Joshua Caleb Bregy

August 2016

The northern Gulf of Mexico has been devastated by recent intense storms. Camille (1969) and Katrina (2005) are two notable hurricanes that made landfall in virtually the same location in Mississippi. However, fully understanding the risks and processes associated with hurricane impacts is impeded by a short and fragmented instrumental record. Paleotempestology could potentially use modern analogues from intense storms in this region to extend the hurricane record back to pre-observational time. Existing empirically-based models can back-calculate surge heights over coastal systems as a function of transport distance, particle settling velocity, and gravitational acceleration. We collected cores in a pond (3) and adjacent beach (1) in Hancock County, Mississippi. Loss-on-ignition and grain-size analyses were conducted on cores in the context of a Bayesian statistical age model using $^{137}$Cs and $^{14}$C dating. Using Camille/Katrina to calibrate the archive, similar coarse-grained deposits were identified, and inverse sediment transport models calculated paleosurge intensities similar in magnitude to Camille over the 2500 year record. However, these are conservative estimates, as the shoreline was further seaward from its modern location approximately
700 yr BP. Our multi-millennial annual average landfall probability (0.48%) closely matches previously published studies from the Gulf of Mexico, indicating that intense hurricanes have not varied over these timescales. Over centennial timescales, active intervals occurred between 900 to 600 and 2200 to 1900 yr BP, and quiescence between 1900 to 900 yr BP. Comparison with previously published sites suggests southerly shifts in the Loop Current may be responsible for regional variability.
ACKNOWLEDGMENTS

First, I would like to express my gratitude to my committee chair, Dr. Davin Wallace, and my other committee members, Drs. Vernon Asper and Grant Harley. Their constant guidance and support throughout the duration of both this research and my time at the University of Southern Mississippi have been invaluable resources. They have helped me discover my niche in the scientific community, and as I take the next step in my career, I am sincerely grateful for the pivotal role my committee has played.

Second, I would like to thank the individuals that helped either in the field, the lab, or while writing this manuscript. Dr. Davin Wallace, Justin Blancher, Clayton Dike, and Victoria Young: I appreciate your help with fieldwork, either by actually collecting cores or loaning equipment to me that made fieldwork possible. Valerie Cruz: Thank you for answering my constant questions regarding the instruments in the lab. I also want to thank Kelsey Kuykendall and Dr. Eric Powell for their expertise in bivalve taxonomy, which was useful for a shell valve found in one of my cores. Finally, I want to thank Jesse Chambliss and Kaitlin Doucette for proofreading my manuscript.

Finally, I would like to thank the Mississippi Department of Marine Resources for granting me a sampling permit and the National Academy of Sciences for providing funding.
DEDICATION

This thesis is dedicated to my loved ones, friends and family alike, all of whom have been an unwavering source of support and guidance. Without them, I would not be who I am today.
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<tbody>
<tr>
<td><em>cal yr BP</em></td>
<td>Calibrated Years Before Present (1950)</td>
</tr>
<tr>
<td><em>CE</em></td>
<td>Common Era</td>
</tr>
<tr>
<td><em>ENSO</em></td>
<td>El Niño/Southern Oscillation</td>
</tr>
<tr>
<td><em>EOC</em></td>
<td>End of Core</td>
</tr>
<tr>
<td><em>ITCZ</em></td>
<td>Intertropical Convergence Zone</td>
</tr>
<tr>
<td><em>LOI</em></td>
<td>Loss-on-Ignition</td>
</tr>
<tr>
<td><em>NASH</em></td>
<td>North Atlantic Subtropical High</td>
</tr>
<tr>
<td><em>NAO</em></td>
<td>North Atlantic Oscillation</td>
</tr>
<tr>
<td><em>NCDC</em></td>
<td>National Climatic Data Center</td>
</tr>
<tr>
<td><em>NHC</em></td>
<td>National Hurricane Center</td>
</tr>
<tr>
<td><em>NOAA</em></td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td><em>NWS</em></td>
<td>National Weather Service</td>
</tr>
<tr>
<td><em>PRM</em></td>
<td>Pearl River Marsh</td>
</tr>
<tr>
<td><em>SLOSH</em></td>
<td>Sea, Lake, and Overland Surges for Hurricanes</td>
</tr>
<tr>
<td><em>SPLASH</em></td>
<td>Special Program to List the Amplitudes of Surges from Hurricanes</td>
</tr>
<tr>
<td><em>SSB</em></td>
<td>Silver Slipper Beach</td>
</tr>
<tr>
<td><em>SST</em></td>
<td>Sea Surface Temperature</td>
</tr>
<tr>
<td><em>SSW</em></td>
<td>Silver Slipper West</td>
</tr>
<tr>
<td><em>TOC</em></td>
<td>Top of Core</td>
</tr>
<tr>
<td><em>USCGS</em></td>
<td>United States Coast and Geodetic Survey</td>
</tr>
<tr>
<td><em>USGS</em></td>
<td>United States Geological Survey</td>
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CHAPTER I - INTRODUCTION

1.1 Background

1.1.1 Introduction

The Gulf of Mexico is frequently impacted by intense hurricanes. Among the numerous storms that have affected the area, two hurricanes in particular have left a lasting impact. Hurricanes Camille (1969) and Katrina (2005) were two of the most devastating cyclones to strike the United States, resulting in over $21 billion and $81 billion, respectively, in damages along the Gulf Coast (Pielke et al. 2008). Separated by 36 years, the two hurricanes made landfall in virtually the same location separated only by ~24 km (Fig. 1) near Waveland, MS (Camille) and Pearlington, MS (Katrina). Both strengthened to category 5 intensity on the Saffir-Simpson Hurricane Wind Scale, with maximum sustained wind speeds reaching 277.8 km/h (Kieper et al. 2016) and 273.5 km/h (Graumann et al. 2005) for Camille and Katrina, respectively. Camille remained at category 5 intensity at landfall (Kieper et al. 2016), while Katrina weakened to a high-end category 3 storm before its third landfall (Graumann et al. 2005).
Figure 1. Tracks and landfall locations of Hurricanes Camille and Katrina.

Hurricane track data is from the National Climatic Data Center (NCDC).
Although Camille was more intense than Katrina by atmospheric standards, with minimum barometric pressures of 900 hPa and 920 hPa, respectively, the storm surge of Katrina was generally greater than that of Camille (Graumann et al. 2005; Fritz et al. 2008). Post-storm surveys in Mississippi estimate maximum storm surges around 6.9 m for Camille in Pass Christian, MS (Liu 2004b; Fritz et al. 2008). Estimates range from 10.1–10.4 m for Katrina in Waveland, MS and Biloxi, MS with areas immediately surrounding Bay St. Louis ranging from 7–10 m (Fritz et al. 2008). Averages for Katrina were 7.5–8.5 m elsewhere along the northern Gulf Coast (Irish et al. 2008). This demonstrates that wind speed is not the sole factor influencing storm surge (Weisberg and Zheng 2006; Irish et al. 2008; Peek and Young 2013).

Hurricane size is also an important driving force behind storm surge (Irish et al. 2008) as is evident when comparing the compact Camille with the larger Katrina. Needham and Keim (2014) found that there was a positive relationship between the hurricane wind swath sizes and surge heights, while the radius of maximum winds are inversely related to surge magnitude, further highlighting the role that size plays—along with intensity and organization—in generating catastrophic surges. Interestingly, Hurricanes Camille and Katrina are notable exceptions to this observation (Needham and Keim 2014). Additionally, processes occurring prior to landfall may influence storm surge. During Katrina, waves generated while the storm was a category 5 were thought to be present at the time of landfall (Fritz et al. 2008) despite downgrading to a category 3. An assortment of other factors play a role in storm surge, including bathymetry (Emanuel et al. 2004; Morton 2010; Weaver and Slinn 2010), coastal geomorphology (As-Salek 1998; Irish et al. 2008; Rego and Li 2009; Peek and Young 2013), and hydrodynamic
processes (As-Salek 1998; Fritz et al. 2008; Irish and Resio 2010; Mori et al. 2014). As such, the storm surge characteristics often show substantial variability from one cyclone to another. However, the most intense events are also the rarest, and the unreliable, fragmented instrumental record only offers a short glimpse into the past.

Our understanding of hurricane impacts can be aided through the field of paleotempestology, which examines proxies containing storm signatures to extend storm records to centennial and millennial timescales (Liu and Fearn 1993, 2000a, 2000b; Donnelly et al. 2001; Nott 2003; Savrda and Nanson 2003; Liu 2004a, 2004b; Donnelly and Woodruff 2007; Elsner et al. 2008; Woodruff et al. 2008; Mann et al. 2009; Nott et al. 2009; Otvos 2011; McCloskey and Liu 2012a, 2012b; Brandon et al. 2013; Brown et al. 2014; Wallace et al. 2014; Burn and Palmer 2015; Donnelly et al. 2015; Ercolani et al. 2015; Trouet et al. 2016). However, no long-term site currently exists using both Camille and Katrina as analogues in the northern Gulf of Mexico, so our understanding of how frequently Camille/Katrina-like storms occur remains limited. Although occurring about 10 years ago, many deposits formed by Katrina have either degraded or fully disappeared chiefly due to bioturbation (Reese et al. 2008; Otvos 2011). Likewise, Camille left behind numerous deposits throughout coastal Mississippi (Liu 2004b); however, much of the record has become largely bioturbated in areas like the Pearl River Marsh (PRM) (Reese et al. 2008) and the Mississippi Sound (Bentley et al. 2002). Coastal lakes (Figs. 3) have been demonstrated as suitable long-term sites, as they offer the highest preservation potential due to their proximity to coarse sediment sources, while remaining virtually free from tidal and riverine activity (Otvos 1999; Hippensteel 2008; Wallace et al. 2014).

Consequently, there are a number of remaining questions. For example, are these coastal
lakes suitable for long-term preservation where Hurricanes Camille and Katrina can serve as modern analogues for studies in paleotempestology in the north-central Gulf of Mexico? Is there variability of Katrina/Camille-like storm events in the northern Gulf of Mexico over centennial to millennial timescales?

Given the uncertainty with the short instrumental-observational record, answering these questions will be paramount toward a better assessment of hurricane risk along the northern Gulf Coast, in addition to refining models used for future hurricane impacts under different climate change scenarios. Moreover, identifying a long-term paleotempestological record of intense storms in this region will aid in our understanding of factors driving intense hurricane variability. We hypothesize that shallow coastal ponds in Mississippi contain storm deposits associated with Hurricanes Katrina and Camille that serve as modern analogues, and therefore are suitable locations for long-term intense storm bed preservation.

1.1.2 Storm Sediment Dynamics and Characteristics

1.1.2.1 Landfalling hurricane processes. When hurricanes impact coastal environments, sediment can be reworked, transported, and/or deposited in coastal and marine environments due to the heightened wave energy (Fig. 2). In many of the strongest storms, an overwash event will occur in one of two forms: breaching and non-breaching (Wang and Horwitz 2007). The former event transports water and sediment behind the berm as a result of rising water-levels due to storm surge and waves (Buynovitch and Donnelly 2006; Wang and Horwitz 2007). While the latter event also transports sediment, there is no barrier breaching that occurs due to direct marine connection (Wang and Horwitz 2007).
Overwash leads to intruding sediment which forms a deposit (washover/washover fans) of generally coarser sediment on top of the already present backbarrier substrate (Liu and Fearn 2000a; Buynevich and Donnelly 2006; Wang and Horwitz 2007; Wallace 2015a, 2015b). The extent of this layer is dependent on different factors like sediment availability, sediment composition, sediment size, hydrodynamics, characteristics of the hurricane, and bathymetry (Donnelly et al. 2006; Wallace et al. 2014). Depending on the storm and coastal environments present, both of these overwash types can occur, which often leads to a mixture of erosion and deposition of sediment from barrier islands to marshes further inland (Fig. 2).

In addition to overwash, other processes may impact coastal systems as a hurricane makes landfall (Fig. 2). Large volumes of precipitation are characteristic of hurricanes. In some cases, rainfall quantities can be significant enough to alleviate droughts along the storm track (Maxwell et al. 2013); however, more often than not, severe—and sometimes life-threatening—inland flooding (Fig. 2) occurs as storms move further onshore (Rappaport 2000; Buckley et al. 2009). This excessive rainfall can trigger landslides (Fig. 2) along the storm path (Chang et al. 2008; Yumul et al. 2012), increasing the risk of mass wasting in landslide-prone locations (Wieczorek et al. 2006). Finally, the waters forced onshore due to surge processes recede into marine environments after a storm. Sediment that has been eroded may be transported offshore (Wallace and Anderson 2013) and along coastal environments via backwash (Fig. 2).
Figure 2. Processes during a landfalling hurricane.

Schematic illustrating the processes (yellow arrows) of a landfalling hurricane on coastal environments (modified from Liu 2004a; Wallace et al. 2014). Note the locations of sediment cores from this study (SSB 1 and SSW 2) and associated coastal pond (gray) and shoreface (yellow) depositional environments.

Understanding the processes associated with landfalling hurricanes has refined paleotempestological methods to better understand storms on centennial to millennial timescales. This is primarily achieved by capitalizing on the multiple proxies that may be captured in coastal environments such as coastal lakes and marshes where washover fans (Liu and Fearn 1993, 2000a, 2000b), marine microfossils consisting of diatoms, dinoflagellates, and foraminifera (Hippensteel and Martin 1999; Liu 2004b, Lu and Liu 2005; Pilarczyk et al. 2014, 2016), and geomorphic features like beach ridges (Nott et al. 2009; Williams 2013) and scarps generated by hurricanes (Buynevich et al. 2007) may be found. Although other proxies exist and have provided records of intense hurricanes, i.e. tree rings (Miller et al. 2006; Rodgers et al. 2006; Trouet et al. 2016), shipwreck rates (Trout et al. 2016) and δ18O signals in corals (Hetzinger et al. 2008) and speleothems (Frappier et al. 2007), the records provided by overwash deposits are by far the most abundant and have largely yielded the best millennial-scale chronologies (Liu 2004b).

Use of overwash layers have frequently provided detailed records of storms (Liu 2004b;
Wallace et al. 2014) as the relative flooding intensity may be reconstructed by examining the lithology (Woodruff et al. 2008; Keen et al. 2012; Brandon et al. 2013). The success of this proxy is predicated on the idea that the high energy levels associated with intense hurricanes can transport coarse-grained sediment. As storm surge overtops barriers, the coarser materials are transported and deposited in coastal environments characterized by fine-grained sedimentation, i.e. ponds, lagoons, and marshes (Liu and Fearn 2000a; Wallace et al. 2014). The results often are coarse layers interspersed between fine-grained sediments, which may be rich in organic matter (Liu and Fearn 2000a; Woodruff et al. 2008; Wallace et al. 2014). The use of modern analogue overwash deposits may be used to constrain and calibrate models used for prehistoric storm reconstruction. Ultimately, this can extend the hurricane record and show changes in hurricane activity and associated climatic controls on varying spatiotemporal scales, such as the strike frequency along different coastlines (Liu and Fearn 2000a, 2000b; Donnelly et al. 2001; Wallace and Anderson 2010; Woodruff et al. 2008).

1.1.2 Transport and sediment characteristics. In general, sediment can range from boulder-size (≥256 mm) to grains that are <1 mm (sands, silts, and clays) (Wentworth 1922). Size classes on this scale reflect different levels of energy in the environment. Larger grains need higher energy to be transported, while smaller particles generally settle out of suspension during fair-weather conditions. In order for sediment to undergo suspension and transportation, a fluid must exhibit shear stress on the particle. Initial movement of particles occurs when the boundary shear stress ($\tau_b$) approaches or equals the critical shear stress ($\tau_{cr}$), and suspension occurs once $\tau_b > \tau_{cr}$ (Jaffe and Gelfenbuam 2007):
\[
\tau_b = \rho_w u^2 \\
\tau_{cr} = \rho_w u_{cr_i}^2
\]

Where \(\rho_w\) is water density, \(u^*\) is the shear velocity, and \(u_{cr_i}\) is the critical shear velocity that is necessary for size class \(i\) to begin moving (Jaffe and Gelfenbuam 2007).

Hurricanes tend to increase wave orbital energies and velocities (Kennedy et al. 2008; Miles et al. 2015), allowing larger grain size transport (Allison et al. 2005). For example, Hurricane Lili (2002, category 4) had wave spectral energy and orbital velocities along the floor that reached 220 m²/Hz and 0.2 m/s, respectively, resulting in a deposit that became progressively poorly sorted as depth increased in the Atchafalaya subaqueous delta (Allison et al. 2005). With more intense surges, higher values are generally expected, as was the case during Hurricane Camille with bottom velocity values peaking near 2 m/s per Advanced Circulation Model estimates (Bentley et al. 2002) as well as the 1.2 m/s velocities measured during Hurricane Katrina along the Louisiana continental shelf before the instrument failed (Dail et al. 2007). It should be noted that the largest grain size available for transport varies between environments. In the case of the Mississippi coast, the coarsest grain sizes available are typically in the sand fraction (0.062– 0.500 mm) (Sawyer 2001; Lisle and Comer 2011).

1.1.2.3 Tempestite formation and preservation. Although a storm can transport large volumes of coarse sediment, only certain environments will enable tempestite preservation. Site selection is critical in order to obtain a reliable paleotempestological record. There are several important factors to consider: bioturbation (Bentley et al. 2006; Hippensteel 2011), sedimentation rate (Wallace et al. 2014), proximity to other possible
sources of deposition and erosion (e.g. non-storm events, rivers, tidal inlets, etc.) (Otvos 1999; Liu 2004b; Bourrouilh-Le Jan et al. 2007; Hippensteel 2008, 2011), and location relative to landfall (Otvos 1999, 2011). Bioturbation disturbs event layers as organisms burrow and displace sediment. In environments with high biological activity, event layers can be completely erased or false signatures could develop (Hippensteel and Martin 1999; Bentley et al. 2006; Hippensteel 2008, 2011; Wallace et al. 2014). Anoxic environments, however, reduce bioturbation because biological activity is virtually nonexistent. Coastal lakes and lagoons often experience anoxic conditions, whether permanently or seasonally, due to stratification or limited exchange rates controlled by physical processes and bathymetry (Sullivan et al. 2013), allowing for greater preservation potentials in these environments.

Sedimentation rates are also important for tempestite preservation. Generally, environments with higher sedimentation rates are favorable for preservation through preventing event layers from amalgamating and becoming indistinguishable from one another (Wallace et al. 2014). However, ideal sites must be limited in their interactions with other depositional and/or erosional events and features, such as from rivers, tidal activity, and even tsunamis, all of which could yield sedimentology similar to storm deposition. Non-cyclonic events, e.g. frontal systems and tsunamis, can erode and potentially rework storm deposits (Bourrouilh-Le Jan et al. 2007; Morton et al. 2007; Boldt et al. 2010). Additionally, false signatures could develop, making distinguishing between hurricanes and other events complicated (Febo et al. 2002; Morton et al. 2007).

Finally, choosing sites based on their relative location to the event (Otvos 1999, 2011; Wallace et al. 2014) and distance from a coarse sediment source is imperative.
Sampling too proximal can often yield an amalgamation of coarse grains, while sampling too distal will not provide a complete event record (Wallace et al. 2014).

Low energy environments, like coastal lakes, marshes, and back barrier island environments, are generally best at tempestite preservation (Donnelly et al. 2001; Otvos 2011; Wallace et al. 2014). Along the northern Gulf Coast, storm deposits can be found in lagoons along the northern side of barrier islands (Otvos 2011), in protected estuaries (Bentley et al. 2002; Febo et al. 2002), and in coastal lakes (Liu and Fearn 1993, 2000a, 2000b; Liu 2004b). Both Petit Bois Island and Dauphin Island in the Mississippi Sound contain washover deposits from Katrina, in addition to previous storms (Otvos 2011). Older storm deposits, including Camille, have been recorded on the backside of barrier islands located further west in the Mississippi Sound, such as Horn and Ship Islands (Bentley et al. 2000, 2002; Liu 2004b; Otvos 2011). A few years after Hurricane Katrina, layers could still be seen in many cores from transects of the PRM, MS/LA (Reese et al. 2008). Despite many of the cores containing distinct Katrina storm layers, previous storms, such as Camille, are difficult to distinguish using organic content (Reese et al. 2008). However, many of these environments are incapable of reliably extending the geologic record due to subsequent erosion of the deposits. Therefore, the presence of preserved modern storm beds to this day would be indicative of an ideal site for deposit preservation, which could yield a long-term hurricane record.

1.1.3 Numerical Models

1.1.3.1 Inverse modeling. Numerical models have been developed to reconstruct historical and paleo-storm surge using sediment transported by storm surge. Moore et al.
(2007) developed a model (Eq. 3) that demonstrates the relationship between the time it takes for sediment to settle out of the water column and the maximum transport time:

\[ \frac{h}{w_s} = t = \frac{x_L}{U} \]  

Equation 3 uses particle settling velocity that is represented by \( w_s \), \( h \) is height from the flow top to bed, \( t \) is settling time, \( x_L \) is the distance between source to point of deposition of the advected sediment, which is ultimately controlled by a depth-averaged vertical velocity flow \( (U) \), i.e. the law of the wall (Moore et al. 2007). The particle settling velocity may be calculated via a universal equation (Ferguson and Church 2004) where \( w_s \) velocity is a function of the particle diameter \( (D) \):

\[ w_s = \frac{R g D^2}{(C_1 v) + (0.75C_2 R g D^3)^{1/2}} \]  

The specific gravity of an immersed particle is represented by \( R \), \( g \) is the acceleration due to gravity, \( v \) is the fluid’s kinematic velocity, and both \( C_1 \) and \( C_2 \) are constants dependent on particle shape (Ferguson and Church 2004). For smooth spheres, \( C_1 = 10 \) and \( C_2 = 0.4 \), while \( C_1 = 24 \) and \( C_2 = 1.2 \) for angular grains (Ferguson and Church 2004). For particles that vary in shape, but are at neither extreme, \( C_1 \) and \( C_2 \) are approximately equal to 18 and 1.0, respectively (Ferguson and Church 2004). Typical values used along the Gulf Coast are \( R = 1.65 \text{ g/cm}^3 \) (for quartz), \( C_1 = 18 \), and \( C_2 = 1 \) (Wallace and Anderson 2010). The depth-averaged vertical velocity flow may be calculated via the following equation:

\[ U = \frac{u_*}{K} \left( \ln \left( \frac{h}{z_0} - \left( 1 - \frac{z_0}{h} \right) \right) \right) \]  

12
Where $u^*$ is the shear velocity, $K$ is the von Kármán constant, and $z_0$ is the bed roughness length (Moore et al. 2007) that is usually $D_{84}/30$ during hydraulically rough flows (Middleton and Southard 1984). This describes the relationship between the mean turbulent flow velocity at a given point and the distance from that point to the fluid boundary, where the former is proportional to the logarithm of the latter, and is applicable in coastal areas due to the flow being unidirectional and short-lived (Moore et al. 2007; Wallace et al. 2014).

These different sediment transport parameters, with a modified critical flow that moves over a barrier ($U = (gh)^{1/2}$), yield a simplified model of flow depth over a barrier, $\langle h_b \rangle$, developed by Woodruff et al. (2008):

$$\langle h_b \rangle = \left( \frac{x_L^2 w^2}{g} \right)^{1/3}$$

Successful application of this model has been used on several landfall locations containing deposits in the Caribbean and the Gulf Coast (Woodruff et al. 2008; Wallace and Anderson 2010). As such, reconstruction of storm surge from modern, historical, and prehistoric hurricanes can be achieved with this model. This method essentially quantifies relative flooding intensity—in this case storm surge—from a deposit, independent of storm intensity (Woodruff et al. 2008; Wallace and Anderson 2010; Wallace et al. 2014). In addition to inversely modeling storm surge, Brandon et al. (2013) developed a relationship using grain size to back-calculate wind speeds. This provides an idea of storm intensity by applying a Saffir-Simpson category to the deposit; however, a straightforward relationship is not always apparent. Camille and Katrina serve as prime examples.
of this idea; at landfall, Camille was two categories higher than Katrina, yet the latter had
da higher maximum storm surge in the impacted regions. Therefore, storm surge may also
serve as a strong metric for storm intensity, and as such, it will be the focus of this study.

1.1.3.2 SLOSH model. Spearheaded by the National Weather Service (NWS), the
SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model was developed to
improve storm surge forecasting for hurricanes approaching the coast. SLOSH is
currently maintained by the National Hurricane Center (NHC), which disseminates model
outputs to emergency management officials for hazard preparedness and decision-
making. The model was a stark improvement from previous models, notably its
predecessor SPLASH (Special Program to List the Amplitudes of Surges from
Hurricanes), because it permitted inland inundation rather than remaining restricted to
shelf environments (Jelesnianski et al. 1992). Model functionality was largely improved
by the use of a polar grid for increased resolution and by keeping several non-linear terms
present in the equations of motion (Jelesnianski et al. 1992). SLOSH now allows for
elliptical and hyperbolic basin grids (Conver et al. 2008). As such, surge in coastal
environments, including local scales, can be estimated for both static and virtually real-
time situations.

Model operation requires two inputs: wind field parameters of the storm and
characterization of the SLOSH basin (Houston et al. 1999; Conver et al. 2008). Wind
field parameterization is achieved by incorporating storm motion (forward speed and
track data), atmospheric pressure, and storm size (Houston et al. 1999). The second input
is the SLOSH basin, of which there are 38 basins as of 2008 (Conver et al. 2008).
Defining SLOSH basins consists of establishing a grid (polar, elliptical, or hyperbolic)
and identifying hydrographic, bathymetric, and topographic features characteristic of a specific location (Jelesnianski et al. 1992; Houston et al. 1999; Conver et al. 2008). Physical equations serving as the framework of the model may then be modified accordingly to best represent the area of interest.

Model outputs may deviate from observed surge values (Zhang et al. 2008; Melton et al. 2010) due to the dynamic nature of hurricanes and coastal environments as well as earlier iterations not taking flooding due to inland precipitation into account (Houston et al. 1999). Although SLOSH has some tendencies to over-predict storm surge, there have been cases where surge values were under-predicted by the model, with Hurricane Ivan serving as a notable example (Melton et al. 2010). Because the modeled landfall differed by 15.5 km from the actual landfall, predicted and actual storm surge values were also markedly different from one another (Melton et al. 2010). Historical simulations of SLOSH have also yielded similar results, despite the wealth of information gathered for each storms. When simulating surge from Hurricane Hugo, values were also under-predicted, while model outputs for Hurricane Andrew coincided well with observed storm surge values (Zhang et al. 2008). Additionally, Zhang et al (2008) ran simulations for Hurricane Camille, with model outputs over-predicting storm surge (maximum storm surge height = 7.4 m) at the landfall site, likely due to missing meteorological data that would otherwise serve as key input parameters. In either case, the model still serves as the primary source of inundation forecasting in use by NHC, and may be frequently updated to best reflect surge intensity and extent as a hurricane approaches the coast. Furthermore, output values may then be validated by observations from post-storm surveys, which subsequently, indicates if and how the model should be
modified for future scenarios. Post-storm runs of SLOSH for Katrina yielded similar results as those seen during post-storm surveys, with at least 70% of SLOSH values within a less than 0.5 m range of survey observations (Rappaport et al. 2009). Ultimately, the inaccuracies seen in SLOSH combined with the fragmented and short instrumental record suggests that our understanding of cyclone impact dynamics remains limited. This is especially concerning as climate change continues to threaten coastal populations, and it stresses the point that turning to the geologic record for answers is critical in order to fully understand intense hurricanes and the associated risks.

1.1.4 Study Goals

In summary, Hurricanes Katrina and Camille have yet to be used as modern analogues for centennial to millennial scale hurricane reconstructions. Our study aims to first understand the sediment transport associated with these events in coastal Mississippi, and subsequently use similar coarse-grained sedimentary deposits from sediment cores to reconstruct the frequency of similar magnitude flooding events in the geologic record. This information can further demonstrate regional variability on different timescales, aiding in our understanding of hurricane-climate interactions.
CHAPTER II - METHODOLOGY

2.1 Study Sites

Previously, coastal waters near Bay St. Louis, MS were sampled for the Camille layer, with the initial deposit estimated to be about 15 cm thick and comprised of a 5 cm sandy basal layer beneath a 5–10 cm muddy layer (Bentley et al. 2000). However, due to frequent bioturbation, only fragmented sandy layers remain at this site as well as several other locations in the Mississippi Sound (Bentley et al. 2002). Several locations in the PRM area have also shown evidence of storms, with results suggesting that the topmost event layer might be a product of Katrina (Reese et al. 2008). However, since initial deposition a decade ago, the layer in the PRM has almost entirely vanished.
Figure 3. Core locations at SSW and SSB.

False color image of the study area. The green circles indicate the locations: three push cores from SSW and one vibracore from the adjacent beach. Surrounding the site is a fringing marsh, while a coarse sediment source is present along the sandy shoreface. Cores (green dots) SSW 1, SSW 2, and SSW 4 were acquired via hammer coring in site SSW. Cores SSW 2 and SSW 4 were taken in the same location in order to collect material for radiometric dating (SSW4) that coincided with the core of record (SSW 2). Core SSB 1 was used to determine the grain sizes available for transport. Digital orthophoto quarter quads from the United States Geological Survey (USGS).

Given these published challenges in obtaining a paleotempestological record in the Mississippi Sound (Bentley et al. 2002) and the fluvially dominated PRM (Reese et al. 2008), we focused our efforts on shallow coastal lakes and ponds (Fig. 3) given these environments generally have the highest preservation potential (Liu and Fearn 1993, 2000a, 2000b; Liu 2004b; Wallace and Anderson 2010; Wallace et al. 2014). There are a series of small coastal ponds along the Mississippi coast that are proximal to a coarse
sand source (Fig. 3). We selected the largest of these systems—which we call Silver Slipper West (SSW)—as the site is virtually free from tidal and riverine activity (Fig. 3). This small coastal pond is separated by a low-lying road (~1 m above sea-level), a small fringing marsh, and a currently nourished beach. Maps of the area (USCDS and USGS 1956) indicate that SSW formed by the mid-1950s at the latest and was therefore impacted by both Camille and Katrina, and that coarse-grained sediment sources are present near the site in the Mississippi Sound (Sawyer 2001). Interactions between the Mississippi Sound and the site remain limited in modern times; however, marine water does enter the pond through permeable subsurface sediment, resulting in brackish conditions.

Pond SSW is a shallow coastal pond with depths ~1 m. Dense vegetation primarily consisting of Spartina spp. and Juncus roemerianus (Eleuterius 1972), and intermittent woody herbaceous plants is present in the fringing marsh surrounding the site. In situ tree stumps were present in the pond, indicating a recent shift in salinity likely due to sea-level rise. Given the isolation of the system from tidal and riverine processes, storm-induced high water events are likely the only mechanism of coarse-grained deposition in the otherwise organic-rich and fine-grained quiescent deposition that is characteristic of SSW.

2.2 Fieldwork

Four cores were collected for further examination in the lab. The transect shown in Figure 3 consisted of three hammer cores (SSW 1, 2, and 4), ranging in length from 82 to 113 cm. Two of the hammer cores (SSW 2 and 4) were taken at the same location in order to obtain additional material (core SSW 4) for radiometric dating. The location of
each core was recorded using handheld GARMIN GPS 12. A 3.8 m beach core (SSB 1—Fig. 3) was collected on the anthropogenically nourished beach to identify sediment sources and determine the grain sizes available for transport. Core SSB 1 was collected using a vibracore system, which creates a standing wave that causes liquefaction and enables penetration and recovery of sandy sediment.

2.3 Sample Analysis

2.3.1 Loss-on-ignition (LOI)

The use of LOI can help identify event layers throughout the core by incinerating organic material. Storm deposits have been shown to notably decrease in organic composition relative to the rest of the core (Liu and Fearn 2000a). This procedure quantifies the percentage of inorganic content present in sediment (Dean 1974). By cutting a core in half and sampling at 1 cm intervals, high resolution data showing variations in the percentage of inorganic sediment can be obtained down core. Samples (~1–2 g) were placed into pre-weighed crucibles, weighed, and dried in an oven at 150 °C for 24 hours before being weighed again after cooling to room temperature. Next, samples were placed into a furnace at 400 °C for 24 hours before cooling to room temperature and being weighed again. Samples were cooled in a desiccator to prevent the samples from acquiring any moisture from the air. The percent inorganic content can then be determined by using Equation 7:

\[ 100 - \left( \frac{W_{\text{dry}} - W_{\text{ash}}}{W_{\text{dry}}} \right) \times 100 \]  

(7)
2.3.2 Percent coarse

Examining the percentage of coarse material with depth is a highly dependable method for distinguishing storm events, because deposits are characterized by coarser sediments than non-storm layers (Liu and Fearn 1993, 2000a, 2000b; Liu 2004b; Wallace et al. 2014; Ercolani et al. 2015). In order to calculate the coarse percentage of a sample, Equation 8 can be used:

\[
\frac{W_{coarse}}{W_{ash}} \times 100
\]  

(8)

Coarse mass is obtained by ridding the sample of fine sediment via sieving. Prior to sieving, samples from the LOI batch were deflocculated in a 6% (NaPO₃)₆ solution for no less than 72 hours. Once deflocculated, a 63 μm sieve was used to separate the coarse grain sizes from fine sediment, i.e. clays and silts, before drying in the oven at 150 °C for 24 hours. Upon drying and cooling, samples were weighed to calculate the coarse percentages. Those that were greater than 5% coarse (based on the lowest values in the core) were selected for further grain-size analysis. This was predicated on the fact that background sedimentation in site SSW is largely fine-grained sediments (clays and silts) as well as organic matter.

2.3.3 Grain-size Analysis

Grain-size analysis is frequently used to identify and characterize layers of coarse-grained peaks (Wallace et al. 2014). Grain-size analysis procedures are modified methods described in Matthews (1991). Sieved (>63 μm) LOI samples >5% coarse from cores SSW 1 and 2 were selected for grain-size analysis, while samples from core SSB 1 only underwent LOI as preparation for the laser particle size analyzer. Samples from both
cores were deflocculated using a 6% (NaPO₃)₆. SSB 1 was sampled in equal intervals within each lithological section. Once the sample soaked for a minimum of 72 hours, it was placed in the Malvern Mastersizer 3000 to determine the grain-size distribution.

Grain-size distributions were sorted into statistical bins: D₁₀, D₁₆, D₅₀, D₈₄, and D₉₀. These different bins serve as percentiles that different grain-sizes fall into for a sample. For example, if the D₉₀ was 175 μm, then 90% of the sediment sampled is smaller than 175 μm. Although all grain-size bins were collected, only the D₉₀ was considered in the analyses as it would best reflect the maximum grain size transported by intense flooding events associated with hurricanes. These statistics in this study are percentiles based only on the coarse (>63 μm) fraction.

2.3.4 Radiometric Dating

2.3.4.1 Cesium-137 dating. Cesium-137 (hereinafter ¹³⁷Cs) is produced through ²³⁵U undergoing nuclear fission due to anthropogenic nuclear activity, such as nuclear detonation. This isotope has a half-life of 30.17 yr and the peak activity serves as a time stamp for CE 1963 ± 2 years, and the onset representing CE 1954 during the Cold War since nuclear testing was banned in the early 1960s (DeLaune et al. 1978; Gehy and Schleicher 1990; Du et al. 2011). Samples were collected in the uppermost 13 cm of core SSW 4 at 1 cm resolution, avoiding coarse-grained material. Analysis was performed by Core Scientific International.

2.3.4.2 Radiocarbon dating. Radiocarbon dating allows for age determination that extends back nearly 50,000 years, with a half-life of ~5700 ± 30 yr (Libby 1946, 1952; Godwin 1962; Dickin 1995). Natural radiocarbon forms in the atmosphere and is cosmogenic in origin, but nuclear testing in the 1950s and 1960s has introduced more ¹⁴C
to the atmosphere (Reimer et al. 2013). Samples were collected from peat in core SSW 4 at 12–13, 36–37, 44–45, 81–82, 91–92, and 93–94 cm, while one Rangia cuneata shell was collected at 282 cm from core SSB 1. These seven samples were sent for analysis at the National Ocean Sciences Accelerator Mass Spectrometry Facility at the Woods Hole Oceanographic Institution. In order to convert $^{14}$C ages to calendar years, calibration is necessary to account for the changing initial concentration of $^{14}$C in the atmosphere through time (Stuiver and Suess 1966). Through significant international collaboration, calibration curves (IntCal13, Marine13, and SHCal13 are the most recent iterations) have been developed to calibrate radiocarbon ages by accounting for changing atmospheric $^{14}$C concentrations (Reimer et al. 2013). The calibration curves developed use multiple proxies, including data from foraminifera, corals, tree rings, and speleothems (Reimer et al. 2013). The most recent dataset was used to calibrate the radiocarbon ages: IntCal13 for peat in core SSW4 and Marine13 for R. cuneata in core SSB 1.

2.3.5 Bacon age-depth model.

Age-depth models can be used to model the age of a core between dated samples. The Bacon program, which is now in version 2.2, is used for this exact purpose (Blaauw and Christen 2011, 2013). Bacon, or Bayesian accumulation, has been used to look at the accumulation record of samples by using dates from radiometric analyses, which are easily incorporated into the script provided as open source that can be run in the R language (Blaauw and Christen 2011, 2013).

Age estimations are obtained by using a Student’s $t$-distribution, thus they remain largely uninfluenced by dates considered to be outliers (Blaauw and Christen 2011,
The Bacon model is able to work with an assortment of absolute date types (Blaauw and Christen 2011, 2013), including $^{14}$C and $^{137}$Cs, which were both used as inputs for core SSW 4. In addition to estimating ages, the Bacon model also estimates accumulation rates in a core. Sedimentation rates are determined by breaking a core into several vertical sections and running multiple Markov Chain Monte Carlo series (Blaauw and Christen 2011, 2013). Generally, sediment deposition and accumulation is assumed to be linear, with changes in sedimentation indicating punctuated events (Blaauw and Christen 2011, 2013). However, the Bacon model infers the accumulation rates by using the different radioisotope dates provided and examining the period between each date (Blaauw and Christen 2011, 2013). By using these dates, changes in sedimentation may be seen through time as the age-depth model is built.
3.1 Core Descriptions

3.1.1 Silver Slipper West

Three hammer cores were collected in a coastal pond in Hancock County, MS (Fig. 3). Cores SSW 1 and SSW 2 were used for lithological replication while core SSW 4 was used to obtain ages for the age-depth model. Core SSW 2 is the core of record because it is the longest sample (113 cm) and was collected at the same location as core SSW 4, which was used for radiometric dating.

The total lengths of core SSW 1, 2, and 4 were 82 cm, 113 cm, and 99 cm, respectively (Fig. 4). In the topmost section of the cores there is a distinct fine-grained inorganic layer from the top of the cores (TOC) to a depth of 9 cm, 10 cm, and 13 cm for cores SSW 1, 2, and 4, respectively. This sediment was largely characterized by predominantly clay and silt-sized particles; however, some very fine to fine-grained sands were present. From ~0 to 2 cm in all cores, the sediment was loosely consolidated, likely due to its location relative to the sediment-water interface. The rest of the fine-grained inorganic layer contained water, but markedly less than the surficial sediment. Considering the high porosity and low permeability of clays, this trend in water content should be expected.

Below the inorganic clays and silts are peat deposits that extend to the end of the cores (EOC) in all cases. There was also an increase in the amount of coarse material in the peat deposits, with very fine to fine-grained sand sizes occurring more frequently than in the inorganic fine-grained layer. No discernable fossils or shells were observed throughout the cores.
3.1.2 Silver Slipper Beach

A 3.8 m vibrocoring (Fig. 5) was collected along the beach shoreface adjacent to pond SSW (Fig. 3) in order to determine the grain-sizes available for transport. The first 89 cm is an anthropogenic sand layer that stems from beach nourishment (Fig. 5). Although fine to medium sands are the predominant grain sizes, there were some observable changes throughout the nourished beach. A brief transition to very fine and fine-grained sands with clay and organic matter occurs at 38–40 cm, coinciding with a vertical black organic horizon at 31–41 cm. From 84 to 89 cm, the predominant grain size transitions to fine sand. At 89–90 cm, a heavily compacted anthropogenic clay layer...
is present (Fig. 5). This clay layer is an experimental practice of nourished beaches as it serves as a cohesive foundation for the sand (Waters et al. 2008).

Beneath the compacted clay layer is the natural sandy shoreface (Fig. 5). While there were large amounts of very fine sands, the sediments became notably muddier than the anthropogenic section above. A mixture of fine and very fine muddy sand was prevalent from 122 to 341 cm, with occasional trace fossils (burrows) and shells interspersed throughout this section. Burrows were found at 213, 248–254, 267–271, and 287–290 cm. Several depths contained shells of *Rangia cuneata*. Large individual shells were found at 186–187 cm and 297 cm, while a smaller shell was present at 288 cm. From 279 to 284 cm, a *R. cuneata* shell hash consisting of small to medium-sized individuals was present (Fig. 5). The Holocene-Pleistocene boundary (Otvos 1975) was located at 345 cm (Fig. 5), based on a transition from sandy mud deposits to characteristic highly compacted, oxidized clays. At this boundary were several burrows full of sandy mud from the Holocene extending into the Pleistocene clays. Below the boundary (~345 cm) were Pleistocene clays likely from the Prairie formation (Otvos 1975) that extended to EOC.
Figure 5. Core SSB 1 lithological description.

The anthropogenic layer extends from TOC to 90 cm, with a heavily compacted clay layer being present at 89–90 cm. Note, a *R. cuneata* shell was collected at 282 cm for radiocarbon dating.

3.2 Lithological Analysis

3.2.1 Percent Inorganic

Examining the amount of inorganic matter can provide insight into environmental processes and change. For cores SSW 1 and 2, inorganic percentages range from 75–97%, with the same trends displayed in both cores (Fig. 6). The inorganic layer from TOC to 9–10 cm had high percentages of inorganic sediment. Some of the highest percentages of inorganic content (SSW 1: 89–97%, and SSW 2: 85–95%) were found within this section. Moving down core into the peat, a small decrease in the relative inorganic content is seen from ~10 to 20 cm before increasing again from ~20 to 82 cm.
Another decrease in inorganic percentages occurs from 82 to 93 cm, increasing again from 93 cm to EOC. In addition to general changes seen in the cores, distinct punctuated oscillations in percent inorganic content are prominent. Particularly large changes are evident at 6– 8 cm, 88– 90 cm, and 101– 103 cm.

Figure 6. SSW 1 and 2 percent inorganic content.

Inorganic content of cores SSW 1 and 2 showing similar trends down core, with oscillations mirroring one another in both depth and magnitude. There are several large changes, most notably at 6– 8 cm, 88– 90 cm, and 101– 103 cm.

3.2.2 Percent Coarse

Examining the percentage of coarse material throughout a core can be useful in identifying storm layers because deposits generally consist of coarser grains. Several relatively coarse layers are present in SSW 2 (Fig. 7) and their depths and D90 grain-size values (Fig. 8) are mirrored in SSW 1. Notable overlapping anomalies in both SSW 1 and SSW 2 are present at the same depths of 3–6 cm within the inorganic clays (Fig. 7). Core SSW 1 shows sediment that is >5% coarse from 1 to 9 cm, with an anomalous peak at 3–6 cm. From TOC to 7 cm, core SSW 2 shows sediment that is >5% coarse, with two anomalous peaks between 2 to 7 cm. These depths have some of the coarsest values
(~32–45%) seen throughout the core. Several peaks, including two with relatively high coarse percentages, are present from ~10 to 40 cm in core SSW 2. The two large peaks from ~10 to 40 cm are generally comparable in magnitude to the peaks found in the inorganic clay layer. In cores SSW 1 and 2, six and seven coarse-grained peaks were identified from 0 to ~40 cm, respectively. Peaks exceeding 5% coarse are absent from ~40 to 65 cm. However, from 65 cm to EOC, we document four (SSW 1) to five (SSW 2) relatively coarse layers (~6–32%). The highly coarse layers have equivalent magnitudes to the large peaks seen at 0–40 cm. In total, 12 coarse peaks were identified in the core SSW 2, with seven at 0–40 cm and five at 65 cm to EOC, with nearly the same in SSW 1. At certain depths, e.g. the peaks from ~35 to 40 cm, the peaks between SSW 1 and SSW 2 are offset by ~1–3 cm, likely due to differences in compaction.

**Figure 7. SSW 1 and 2 percent coarse >63μm.**

The percentage of coarse sediment >63μm for the core of record (SSW 2) and the replication core (SSW 1). The two cores have similar profiles, with the same number of peaks occurring at similar depths. From 0 to 40 cm and 65 cm to EOC, there are a cluster of peaks, while sediment from 40 to 65 cm does not exceed 5% coarse.
3.2.3 Grain-Size Analysis

3.2.3.1 SSW. Depths with values greater than 5% coarse were analyzed for further grain-size statistics for cores SSW 1 and 2. Treatment for percent coarse analysis removed all sediment finer than 63 μm, allowing larger fractions to be examined in detail. The D₉₀ grain-sizes from these layers range from ~155 to 228 μm, and are quite similar for both cores SSW 1 and 2 (Fig. 8). In the inorganic clay layer, the D₉₀ grain-sizes of coarse peaks are 171.7 μm and 179.2 μm at 3–4 and 5–6 cm, respectively. Similar particle sizes are seen in peat layers in the 0–40 cm section. The highly coarse peaks at 11–12 cm and 24–25 cm contain particle sizes—189.8 μm and 182.6 μm, respectively—that exceed the D₉₀ sizes in the inorganic clays. Grain-sizes of the peaks occurring at 65 cm to EOC contain comparable sediment sizes to those seen at the peak from 0 to 40 cm. At 82–83 cm and 88–89 cm, D₉₀ values reach 227.7 μm and 214.9 μm, respectively, and near the threshold between fine and medium-grain sand. However, all grain-sizes are still quite similar to one another (Fig. 8).
Figure 8. SSW 1 and 2 percent coarse and $D_{90}$ grain sizes ($\mu$m).

The percentage of coarse sediment (A and C) >63$\mu$m and the associated $D_{90}$ grain sizes ($\mu$m) (B and D) for the coarse layers in cores SSW 1 and 2. Core SSW 2 (C and D) is the core of record due to its length and proximity to the core used for $^{14}$C and $^{137}$Cs dating (SSW 4). Core SSW 1 is a replication of core SSW 2. The colored horizontal dashed-lines drawn from the coarse percentages to the grain sizes indicate the maximum $D_{90}$ values present in each coarse layer (B and D). A total of 12 peaks were identified in SSW 2, with $D_{90}$ grain-sizes ranging from ~155 to 228 $\mu$m. The background sediment ($\leq$5% coarse) is represented by the dashed black vertical line in A and C.

3.2.3.2 SSB 1. Throughout the core, there is an obvious decrease in the $D_{90}$ grain-size with depth (Fig. 9). Excluding the sample at 36–37 cm, which coincides with the black organic horizon at 31–41 cm, the first half of the nourished beach consists of medium-sized sand grains that range from 345–440 $\mu$m. The bottom half of the anthropogenic beach consists of fine sand grains spanning 111–153 $\mu$m. Below the nourished beach is the natural shoreface, where sediments continue a fining trend. The shoreface sediments at this depth range from 75 to 194 $\mu$m. Generally, the $D_{90}$ particle sizes in SSB 1 match those found in the SSW cores. However, from 218 cm to EOC, the grain-sizes are finer than the coarsest sediment in SSW 2.
Core SSB 1 was taken to determine the $D_{90}$ sizes available for transport. There was a general decrease from medium-sized sands found at the top of the anthropogenic beach (TOC to 90 cm) to fine and very fine (muddy) sand grains at the base of the nourished beach and throughout the natural sandy shoreface. Heavily compacted, oxidized clays were present from 341 cm to EOC, with burrows full of Holocene sediments extending into Pleistocene clay layer.

### 3.3 $^{14}$C and $^{137}$Cs Dating

We obtained seven radiocarbon ages that have been calibrated and are reported in Table 1. The *R. cuneata* shell from 282 cm in the beach core (SSB 1) was dated and yielded a calibrated—using the Marine13 calibration curve (Reimer et al. 2013)—2σ range of 558–662 cal yr BP. The peat was dated from core SSW 4 at depths of 12–13 cm (568–672 cal yr BP), 36–37 cm (920–957 cal yr BP), 44–45 cm (1532–1605 cal yr BP), 81.5 cm (2123–2306 cal yr BP), 91–92 cm (2155–2314 cal yr BP), and 93–94 cm (1950–2113 cal yr BP). The terrestrial calibration curve, IntCal13 (Reimer et al. 2013), was used to calibrate radiocarbon ages from core SSW 4.
Table 1

 Radiocarbon age values for SSB 1 and SSW 4

<table>
<thead>
<tr>
<th>Sample core</th>
<th>Absolute depth (cm)</th>
<th>Sample type</th>
<th>Modern fraction</th>
<th>Modern fraction error</th>
<th>$^{14}$C age</th>
<th>$^{14}$C age uncertainty</th>
<th>Calibration dataset (Reimer et al. 2013)</th>
<th>2σ cal yr BP age</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSB 1</td>
<td>282</td>
<td>Rangia cuneata</td>
<td>0.8778</td>
<td>0.0019</td>
<td>1050</td>
<td>20</td>
<td>Marine13</td>
<td>558– 662</td>
</tr>
<tr>
<td>SSW 4</td>
<td>12– 13</td>
<td>Peat</td>
<td>0.9187</td>
<td>0.0020</td>
<td>680</td>
<td>15</td>
<td>IntCal13</td>
<td>568– 672</td>
</tr>
<tr>
<td>SSW 4</td>
<td>36– 37</td>
<td>Peat</td>
<td>0.8815</td>
<td>0.0019</td>
<td>1010</td>
<td>15</td>
<td>IntCal13</td>
<td>920– 957</td>
</tr>
<tr>
<td>SSW 4</td>
<td>44– 45</td>
<td>Peat</td>
<td>0.8129</td>
<td>0.0016</td>
<td>1660</td>
<td>15</td>
<td>IntCal13</td>
<td>1532– 1605</td>
</tr>
<tr>
<td>SSW 4</td>
<td>81.5</td>
<td>Peat</td>
<td>0.7626</td>
<td>0.0017</td>
<td>2180</td>
<td>20</td>
<td>IntCal13</td>
<td>2123– 2306</td>
</tr>
<tr>
<td>SSW 4</td>
<td>91– 92</td>
<td>Peat</td>
<td>0.7587</td>
<td>0.0016</td>
<td>2220</td>
<td>15</td>
<td>IntCal13</td>
<td>2155– 2314</td>
</tr>
<tr>
<td>SSW 4</td>
<td>93– 94</td>
<td>Peat</td>
<td>0.7739</td>
<td>0.0017</td>
<td>2060</td>
<td>20</td>
<td>IntCal13</td>
<td>1950– 2113</td>
</tr>
</tbody>
</table>

Samples from the inorganic clay layer in the uppermost 12 cm of core SSW 4 underwent $^{137}$Cs analysis, the results of which can be seen in Table 2. $^{137}$Cs activity peaks at 8– 9 cm (0.53 dpm/g), marking 1963 CE ± 2 years (DeLaune et al. 1978). Below the peak, values decrease with depth, while activity shows an inverse relationship with depth above 8– 9 cm.

Table 2

$^{137}$Cs activity values for SSW 4

<table>
<thead>
<tr>
<th>Sample core</th>
<th>Absolute depth (cm)</th>
<th>Activity (dpm/g)</th>
<th>Approximate error (dpm/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSW 4</td>
<td>0– 1</td>
<td>0.31</td>
<td>0.30</td>
</tr>
<tr>
<td>SSW 4</td>
<td>1– 2</td>
<td>0.39</td>
<td>0.37</td>
</tr>
<tr>
<td>SSW 4</td>
<td>7– 8</td>
<td>0.43</td>
<td>0.39</td>
</tr>
<tr>
<td>SSW 4</td>
<td>8– 9</td>
<td>0.53</td>
<td>0.46</td>
</tr>
<tr>
<td>SSW 4</td>
<td>9– 10</td>
<td>0.48</td>
<td>0.46</td>
</tr>
<tr>
<td>SSW 4</td>
<td>10– 11</td>
<td>0.38</td>
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<tr>
<td>SSW 4</td>
<td>11– 12</td>
<td>0.33</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Using the default model settings, the ages from core SSW 4 (Tables 1 and 2) were input into Bacon, producing an age-depth model (Fig. 10) that allows the sedimentation
rates to be calculated (Table 3). Constant and relatively high sedimentation rates (Table 3) are present from 0 to 9 cm (1.6 mm/yr), 12 to 37 cm (0.62 mm/yr), 45 to 81.5 cm (0.61 mm/yr), and 81.5 to 99 cm (0.44 mm/yr). These four periods last from -8 to -65 cal yr BP (1958–2015 CE), 1000 to 600 cal yr BP, 2100 to 1500 cal yr BP, and ~2500 to 2100 cal yr BP, respectively. However, two periods of decreased sedimentation (Table 3) are present from 9 to 12 cm (600 to -8 cal yr BP: 0.049 mm/yr) and 37 to 45 cm (1500–1000 cal yr BP: 0.16 mm/yr).

Figure 10. Age-depth model for core SSW 4.

The age-depth model produced by the Bacon program used $^{137}$Cs and $^{14}$C to identify sedimentation rates. The $^{137}$Cs data (green) indicates 1963 CE + 2 years and the calibrated radiocarbon ages (blue) indicate that our record extends ~2500 cal yr BP. Sedimentation has remained relatively constant, with the exception of the 9–12 cm and the 37–45 cm intervals, where rates decreased to 0.74 mm/yr and 0.16 mm/yr, respectively.
Table 3

*Calculated sedimentation rates*

<table>
<thead>
<tr>
<th>Core Name</th>
<th>Depth (cm)</th>
<th>Age Range (cal yr BP)</th>
<th>Calculated Sedimentation Rate (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSW 4</td>
<td>0–9</td>
<td>-8 to -65</td>
<td>1.6</td>
</tr>
<tr>
<td>SSW 4</td>
<td>9–12</td>
<td>600 to -8</td>
<td>0.049</td>
</tr>
<tr>
<td>SSW 4</td>
<td>12–37</td>
<td>1000 to 600</td>
<td>0.62</td>
</tr>
<tr>
<td>SSW 4</td>
<td>37–45</td>
<td>1500 to 1000</td>
<td>0.16</td>
</tr>
<tr>
<td>SSW 4</td>
<td>45–81.5</td>
<td>2100 to 1500</td>
<td>0.61</td>
</tr>
<tr>
<td>SSW 4</td>
<td>81.5–99</td>
<td>~2500 to 2100</td>
<td>0.44</td>
</tr>
</tbody>
</table>
CHAPTER IV - DISCUSSION

4.1 Depositional Patterns

We interpret the inorganic fine-grained sediment in the top of the SSW cores as modern bay clays, indicative of a shallow, low-energy environment. Likewise, we interpret the peat deposits as a low-energy paleomarsh which existed prior to the open water. From core SSB 1 (Fig. 9; Table 1), sand grain sizes are available for transport in both the anthropogenic beach and the sandy shoreface in near modern day positions for at least ~700 cal yr BP. While there is some difference in grain sizes available for the anthropogenic beach (111–440 μm) and the sandy natural shoreface below (75–159 μm), these values are relatively similar. Given the age of the sandy shoreface environment adjacent to the pond, this indicates that coarse material before ~700 cal yr BP was likely sourced from a similar environment further seaward of the modern beach. This is not surprising given that sea level has risen about 1 m over the last ~2500 years (Anderson et al. 2014), thus the low bathymetric relief along the Mississippi Gulf Coast would likely result in dramatic changes in shoreline location (Nicholls and Cazenave 2010) even with rates of sea level rise as low as 0.4–0.6 mm/yr from 2000–0 cal yr BP (Törnqvist et al. 2004; Anderson et al. 2014).

Site SSW has been a coastal pond since the early 1950s at the latest (USCGS and USGS 1956), meaning that it was present for both Hurricanes Camille and Katrina. Given the peak in $^{137}$Cs activity indicating 1963 CE ± 2 years just below the first Camille/Katrina coarse layers, the slow background sedimentation of the bay clays, i.e. without the influence of storms (0.1 mm/yr), low LOI values, high percentages of coarse sediment, high $D_{90}$ values, we determine that Camille and Katrina left deposits that are
nearly amalgamated as one coarse-grained peak in core SSW 2, as their deposition would have only been separated by 3.6 mm. In core SSW 2, the Katrina deposit occurs at 3–4 cm (D_{90} = 171.7 \mu m) and the Camille deposit occurs at 5–6 cm (D_{90} = 179.2 \mu m) (Figs. 7, 8). Core SSW 1 shows evidence of Camille and Katrina as a single peak (Figs. 7, 8). It is the thickest sand deposit in the entire core, meaning it likely represents two events. Given these two storms were the most intense events to impact the area during the time of pond formation, we determined that these deposits in cores SSW 1 and 2 represent modern analogues of intense storm deposition for this system. Sandy layers at depth, therefore, are interpreted as prehistoric storm events of likely similar flooding magnitudes. Two important caveats should be mentioned. First, the source of sand for the Camille/Katrina layer was likely closer in proximity to the pond than the source for the sandy layers deeper in the core due to the sandy shoreface environment likely being significantly seaward of the environment documented in core SSB 1. Consequently, the deeper coarse-grained peaks deposited in the core likely represent equal or greater intensity flooding events. Furthermore, we interpret discrete peaks as individual storms deeper in the section. However, given the low sedimentation rates throughout the core, coarse peaks possibly represent multiple events if they impact the same area within a relatively short time span. For example, the two deposits present at 82–89 cm never return to background coarseness (<5% coarse) and likely represent two storms that have amalgamated, similar to the Camille-Katrina deposits. Thus, coarse-grained peaks at depth likely represent a minimum estimate of high intensity flooding events.
4.2 Camille and Katrina as Modern Analogues

We can further understand sediment transport distances through the use of the Woodruff et al. (2008) inverse transport model. Assuming \( \langle h_b \rangle = 8.70 \text{ m} \)—the highest reconstructed post-Katrina storm surge value at SSW (Fritz et al. 2008)—and \( w_s \) is calculated (Ferguson and Church 2004) as 0.0196 m/s \( (D_{90K} = 172 \mu \text{m}, R_{\text{quartz}} = 1.65 \text{ g/cm}^3) \), the computed sand transport distances \( (x_L) \) would be \( \sim4100 \text{ meters} \). Assuming \( \langle h_b \rangle = 4.88 \text{ m} \)—based on the highest SLOSH runs for Camille at SSW (NHC 2015)—and \( w_s \) is calculated (Ferguson and Church 2004) as 0.0208 m/s \( (D_{90C} = 179 \mu \text{m}, R_{\text{quartz}} = 1.65 \text{ g/cm}^3) \), the computed sand transport distances \( (x_L) \) would be \( \sim1624 \text{ meters} \). These transport distances suggest storms are transporting sand from Mississippi Sound, which is known to contain these grain sizes \( \sim1–4 \text{ km offshore} \) (Sawyer 2001). Based on the \( D_{90} \) range \( (154–228 \mu \text{m}) \) for all prehistoric coarse grained peaks in the paleomarsh section, and assuming the minimum computed transport distances calculated from Camille \( (~1624 \text{ meters}) \), we calculate paleosurges ranging between 4.19–6.16 m for equally high percent coarse and \( D_{90} \) values from sand layers in the paleomarsh section. Given this high flooding threshold required for coarse-grained deposition and the age of these events spanning the last \( \sim2500 \text{ cal yr BP} \), we interpret these anomalies as paleohurricanes, leading to intense flooding the region.

4.3 Long-Term Hurricane Chronology

The results from the radiocarbon ages and age-depth model indicate that a \( \sim2500 \text{ cal yr BP} \) record exists at site SSW (Fig. 10). There are clusters of coarse-grained peaks recorded from 0 to 8 cm, 10 to 37 cm, and 65 to 89 cm (Fig. 8). From the age depth model, intervals of intense flooding occur between 900 to 600 cal yr BP (maximum 2\( \sigma \)
range: 1200–500 cal yr BP (12.5–34.5 cm) and 2200 to 1900 cal yr BP (maximum 2σ range: 2300–1700 cal yr BP) (66.5–88.5 cm) (Fig. 11). Considering the lack of coarse-grained deposition in between, we interpret the interval from 1900 to 900 cal yr BP as a quiescent period in relative intense flooding. If we assume each coarse-grained layer represents one event, then a minimum of 12 intense hurricanes have impacted the area over the last ~2500 cal yr BP (0.48% annual direct landfall probability) (Fig. 11). Given the coarse source was likely further seaward >700 years ago, the storm deposition before this time interval likely represents storms of an even higher relative flooding intensity than Camille/Katrina.

Figure 11. Ages of intense hurricanes in the north-central Gulf of Mexico.

Age-depth model (A) compared to the percent coarse (B) and associated D90 values (C) from core SSW 2. Using the age-depth model, there are a minimum of 12 intense hurricanes (red dashed lines) that have impacted this region over the last ~2500 cal yr BP, yielding an annual direct landfall probability of 0.48%. Two periods of heightened activity are present at 10–37 cm and 65–89 cm, while a quiescent period occurs from 37 to 65 cm. The background sediment (≤5% coarse) is represented by the dashed black vertical line in B.
4.4 Climate Context

By comparing our results with previous paleotempestological studies using a coarse-grained proxy for the Gulf of Mexico, regional and spatial trends in intense hurricane activity over centennial to millennial timescales can be elucidated. In Laguna Madre, Texas, intense hurricane deposits are preserved from ~5300 to 900 cal yr BP (0.46% average annual direct landfall probability) (Wallace and Anderson 2010). Twelve intense hurricanes struck Western Lake, Florida between ~3500 to 500 cal yr BP (0.39% annual direct landfall probability) (Liu and Fearn 2000a). Eleven intense hurricanes impacted Lake Shelby, Alabama between ~3500 to 700 cal yr BP (0.39% annual direct landfall probability) (Liu and Fearn 2000b). Donnelly and Woodruff (2007) reconstructed a 5000 cal yr BP hurricane record from Laguna Play Grande, Puerto Rico, with millennial-scale intervals occurring at 4400–3600 cal yr BP and 2500–1000 cal yr BP.

Our minimum calculated average millennial-scale annual direct landfall probabilities (0.48%) are similar to these previous works, and further suggest that over multimillennial time periods, intense hurricanes have not varied significantly in the Gulf of Mexico (Wallace and Anderson 2010; Wallace et al. 2014).

Over centennial timescales, intense hurricanes have varied in the Gulf of Mexico and Caribbean. The same record from Puerto Rico suggests an active hurricane period extending back from 250 cal yr BP – present (Donnelly and Woodruff 2007). Lane et al. (2011) obtained a record from Mullet Pond, Florida which contains a sedimentological record of low and high threshold events for the last ~4500 cal yr BP with periods of frequent intense hurricane strikes occurring between 3950 and 3650 cal yr BP, 3600 and 3500 cal yr BP, 3350 and 3250 cal yr BP, 2800 and 2300 cal yr BP, 1250 and 1150 cal yr
BP, 925 and 875 cal yr BP, and 750 and 650 cal yr BP. A period of intense storms between ~1700 and 600 cal yr BP is captured in a record from Spring Creek, Florida (Brandon et al. 2013).

Variability in hurricane activity has been linked to several different climatic controls. On annual and decadal scales, it has been demonstrated that El Niño-Southern Oscillation (ENSO) results in heightened hurricane activity during the cold phase in the North Atlantic (Bove et al. 1998; Chu 2004; Smith et al. 2007). Long-term changes to ENSO have been documented (Langton et al. 2008), and some studies suggest this can influence hurricane variability on centennial and millennial timescales (Donnelly and Woodruff 2007; Mann et al. 2009). In the case of our records, the two active periods (2200–1900 cal yr BP and 900–600 cal yr BP) overlap with two periods (3500–1700 cal yr BP and 1000–750 cal yr BP) of more frequent and/or stronger La Niña-like conditions based on sediment cores from Kau Bay in Halmahera, Indonesia (Langton et al. 2008). This long-term ENSO record match those Moy et al. (2002) observed in sediment cores from Laguna Pallcacocha, Ecuador. Other studies indicate that regional and local climatic phenomena also strongly affect hurricane variability by influencing atmospheric circulation patterns and oceanographic conditions (Elsner et al. 2000; Liu and Fearn 2000a; Liu 2004b; McCloskey and Liu 2012b; Brandon et al. 2013; Toomey et al. 2013; Denommee et al. 2014). Changes in the intensity of the North Atlantic Oscillation (NAO), and consequently the position of the North Atlantic Subtropical High (NASH), are linked to variability in hurricane activity (Denommee et al. 2014) due to changes in sea surface temperatures (SSTs) as well as storm tracks and landfall locations (Elsner et al. 2000; Liu 2004b). As the NAO weakens, the Gulf Coast is particularly
vulnerable to major hurricane strikes due to reduced latitudinal recurvature (Elsner et al. 2000; Liu 2004b). Bianchi and McCave (1999) suggest that the NAO displays a quasi-cyclical pattern spanning ~1500 years. Finally, migration of the Intertropical Convergence Zone (ITCZ) is thought to control storm activity and tracks (McCloskey and Liu 2012b; Toomey et al. 2013) primarily through changes in SSTs (Xie et al. 2005) and the West African Monsoon (Landsea et al. 1999). Sediment records have shown that the ITCZ started moving southward during the mid- to late Holocene (Haug et al. 2001; Poore et al. 2004), therefore shifting the bulk of cyclone activity south as well (Toomey et al. 2013).

While global (e.g. ENSO) and regional (e.g. NAO) climate processes clearly influence cyclone activity, the variability between other storm records in the region (Lane et al. 2011; Brandon et al. 2013) and our record cannot be primarily attributed to large-scale climate teleconnections, suggesting that changes in local processes serve as a primary control on hurricanes over centennial timescales in the northern Gulf of Mexico. The Loop Current is thought to be a control on hurricane variability (Brandon et al. 2013) due to its influence on the thermal structure of the Gulf of Mexico (Goni and Trinanes 2003). Changes in abundance of the foraminifer proxy species *Globigerinoides sacculifer* has been linked to variations in the Loop Current (Poore et al. 2003, 2004; Richey et al. 2007). Poore et al. (2004) later linked changes in the extent that the Loop Current intrudes into the Gulf of Mexico to ITCZ migration. Particularly noteworthy is that around 600 cal yr BP, the Loop Current is thought to have migrated south (Poore et al. 2004), corresponding to a decrease in the number of intense hurricanes present in records across the eastern half of the Gulf of Mexico (Lane et al. 2011; Brandon et al. 2013), in
addition to our record along the north-central Gulf of Mexico. The divergence between the centennial-scale records from this region (i.e. Lane et al. 2011; Brandon et al. 2013; this study) during earlier active intervals cannot be solely explained by large-scale climate teleconnections (Brandon et al. 2013) based on current paleoclimate reconstructions. However, the degree of Loop Current penetration (Poore et al. 2004) and its influence on storm activity during active periods shows general agreement between centennial-scale records within this region (Lane et al. 2011; Brandon et al. 2013; this study). This suggests that long-term local processes might serve as the predominant forcing mechanisms behind hurricane variability and therefore can potentially explain the divergence seen during earlier active storm intervals in the Gulf of Mexico. Nonetheless, this highlights the need for longer local, regional, and global paleoclimate records in order to fully understand the dynamic relationship between hurricanes and climate.
CHAPTER V – CONCLUSION

Paleotempestology unlocks information about our past climate by examining sediment records for deposits left behind by intense hurricanes. As a result, this information may be used to understand how intense hurricanes will respond to a changing climate. However, modern analogues are necessary to identify these paleo-events. Our site in Hancock County, MS is a coastal pond that offers a ~2500 year paleohurricane record. Preserved near the surface are modern analogue storm deposits left by Hurricanes Camille and Katrina. Using an inverse model, transport distances of the coarse sediment from Camille and Katrina were back calculated as ~1624 m and 4100 m, respectively. These are realistic distances considering the low bathymetric relief along the Mississippi Gulf Coast and the availability of sand in the Mississippi Sound. The paleohurricanes identified from sediment cores were determined to have paleosurges of 4.19–6.16 m using estimates of transport distances associated with Camille. However, considering that sea-level was at a lower position and the shoreface was more seaward than its present location >700 years ago, the coarse-grained peaks in the older intervals likely represent events with higher relative flooding intensities than Camille/Katrina, and the paleosurge values reported are conservative estimates. Our millennial scale average landfall probabilities (0.48% annual direct landfall probability) are nearly identical to previously published values from Laguna Madre, TX (0.46% average annual direct landfall probability; Wallace and Anderson 2010), Western Lake, FL (0.39% annual direct landfall probability; Liu and Fearn 2000a), and Lake Shelby, AL (0.39% annual direct landfall probability; Liu and Fearn 2000b). This further suggests that over multimillennial
time periods, intense hurricanes have not varied significantly in the Gulf of Mexico (Wallace and Anderson 2010; Wallace et al. 2014).

Over centennial timescales, our hurricane chronology suggests active intense flooding events between 900 and 600 cal yr BP and 2200 to 1900 cal yr BP, with a quiescent period between 1900 and 900 cal yr BP. The relative quiescence documented over the last 600 cal yr BP aligns with the event chronologies produced by similar proxy and resolution studies from Florida (Lane et al. 2010; Brandon et al. 2013; Wallace et al. 2014), indicating that the eastern Gulf of Mexico experienced a climatic shift in storm steering mechanisms after this time. The southerly migration of the Loop Current (Poore et al 2004) around 600 cal yr BP is the most likely explanation. The divergence of the earlier component of storm records in the northern Gulf of Mexico cannot solely be explained by large scale climate teleconnections, e.g. ENSO, as it appears likely that local processes, such as the Loop Current, serve as the primary control on cyclone variability in the Gulf of Mexico. However, it is imperative that we continue to lengthen and refine paleoclimate reconstructions in order to better understand cyclone-climate relationships.
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