Intense Southwest Florida Hurricane Landfalls over the Past 1,000 Years

Christian Ercolani¹, Joanne Muller^{1*}, Jennifer Collins², Michael Savarese¹, Louis Squiccimara¹

1. Department of Marine and Ecological Sciences, Florida Gulf Coast University, Fort Myers, FL, 33965, USA

2. School of Geosciences, University of South Florida, Tampa, FL, 33620, USA

ABSTRACT

Recent research has proposed that human-induced sea surface temperature (SST) warming has led to an increase in the intensity of hurricanes over the past 30 years. However, this notion has been challenged on the basis that the instrumental record is too short and unreliable to reveal long-term trends in hurricane activity. This study addresses this limitation by investigating hurricane-induced overwash deposits (paleotempestites) behind a barrier island in Naples, FL, USA. Paleotempestologic proxies including grain size, percent calcium carbonate, and fossil shells species were used to distinguish overwash events in two sediment cores spanning the last one thousand years. Two prominent paleotempestites were observed in the top 20 cm of both cores: the first identified as Hurricane Donna (1960) whereas an older paleotempestite (1900-1930) could represent one of three documented storms in the early 1900s. An active period of hurricane overwash from 1000–500 yrs. BP and an inactive period from 500-150 yrs. BP correlate with reconstructed SSTs from the Main Development Region (MDR) of the North Atlantic Ocean. We observe an increased number of paleotempestites when MDR SSTs are warmer, coinciding with the Medieval Warm Period, and very few paleotempestites when MDR SSTs are cooler, coinciding with the Little Ice Age. Results

from this initial Southwest Florida study indicate that MDR SSTs have been a key long-term climate driver of intense Southwest Florida hurricane strikes.

Keywords: paleotempestology; Southwest Florida; hurricanes; Main Development Region; barrier beaches

1. Introduction

Understanding fluctuations in hurricane activity has become critically important given the continued population expansion of coastal areas. Due to their powerful winds, high waves, torrential rains and storm surge causing flooding, hurricanes are the single most costly and destructive weather disaster in the United States (U.S.) (Emanuel, 2005). Hurricane damages in the U.S. alone are estimated at \$9 billion every year (mean value for 1950-2008) (Nordhaus, 2010). Recent work by Mendelsohn and Saher (2011) suggests that income and population growth are expected to increase the baseline damage from \$9 to \$27 billion per year by 2100. Furthermore they note that climate change is expected to increase damage by another \$40 billion, with over 85 percent of these impacts expected in Florida and the Gulf Coast region. Florida is particularly vulnerable to hurricanes because it is a peninsula with subtropical warm water on three sides. Typically, hurricanes developing in the Main Development Region (MDR: 10° N to 20° N and 20° W to 60° W) of the North Atlantic (Goldenberg and Shapiro, 1996; Saunders and Harris, 1997) move in a general westward direction across the North Atlantic Ocean, making landfall on Caribbean Sea islands and landmasses along the Gulf of Mexico and Southeastern U.S. seaboard. On average, a hurricane threatens to impact portions of the state of Florida every two years (Malmstadt et al., 2009). This problem is exacerbated by a rapidly increasing population and a densely

populated coastline. Most of Florida's coastline is less than 2.5 m above sea level and at high risk of inundation by rising sea levels (Stockdon et al., 2012).

Several lines of evidence suggest that anthropogenic climate change may substantially influence hurricane activity worldwide. When considering thermodynamic changes alone, research indicates that global hurricane frequency should diminish, but the incidence of high-intensity events will increase (Emanuel et al., 2008). The percentage of high-intensity storms is indeed increasing (Webster et al., 2005; Elsner et al., 2008). In the North Atlantic basin, where records of directly observed hurricanes are longer and generally of better quality, hurricane frequency and intensity correlate strongly with SSTs where storms typically develop (Emanuel, 2005; Elsner et al., 2006; Emanuel, 2007; Holland and Webster, 2007; Saunders and Lea, 2008).

In addition to SSTs, the El Niño-Southern Oscillation (ENSO) influences the formation and pathway of hurricanes (e.g., Bove et al., 1998). ENSO changes have far-reaching impacts, directly affecting global hurricane activity via SST, vertical wind shear, mid-tropospheric relative humidity, low-level relative vorticity, and other factors (Gray, 1984; Gray and Sheaffer, 1991; Goldenberg and Shapiro, 1996; Knaff, 1997; Collins and Mason, 2000). The impact of El Niño and La Niña on hurricane variability in the North Atlantic basin has been studied widely, with storm frequencies, durations, and intensities generally decreasing when El Niño conditions are present (Landsea et al., 1999) and increasing when La Niña conditions occur (Xie et al., 2005; Lupo et al., 2008). Furthermore, the favored genesis regions and storm tracks are impacted (Elsner and Kara, 1999) with decreased activity in the MDR during El Niño conditions. This in turn leads to changing landfall patterns along the U.S. and Caribbean coastlines, with risk of more frequent and stronger strikes during La

Niña conditions, less frequent and weaker strikes during El Niño events (O'Brien et al., 1996; Pielke and Landsea, 1999; Tartaglione et al., 2003; Smith et al., 2007), and moderate risk noted during ENSO neutral conditions (Bove et al., 1998). For this reason, ENSO is used as a critical predictor in empirical forecasting of hurricane frequency in a given year.

Though prior work highlights the importance of understanding hurricane dynamics, our understanding of the processes that control the formation, intensity, and track of hurricanes is still restricted (Goldenberg et al., 2001). Most limiting is the 161-year old North Atlantic Basin hurricane record (Landsea et al., 2013), a record too short to reveal long-term trends in hurricane activity (centuries to millennia). This limitation can be overcome using paleotempestology, a relatively new field that identifies past hurricane activity through use of geological (e.g. Liu and Fearn, 2000) and biological (Elsner, 2007) proxies. Most paleotempestological records are created using preserved hurricane overwash signatures. In these studies, the combination of storm surge and waves overtopping barrier beaches produces overwash signatures in back-barrier environments (Schwartz, 1975; Donnelly et al., 2001). Some of the best sites for preserving overwash deposits, and thus archives of hurricane landfalls, are coastal lakes, lagoons, and marshes (Liu and Fearn, 1993; Hippensteel and Martin, 1999; Liu and Fearn, 2000; Donnelly et al., 2001; Donnelly et al. 2004). The sediment and microfossils from these locations have been used to document prehistoric storm frequency and recurrence intervals (Hippensteel and Martin, 1999; Donnelly et al., 2001; Scott et al., 2003; McCloskey and Keller, 2009; Lane et al., 2011).

Paleotempestological analyses have been undertaken along the northern U.S. Gulf Coast (e.g. Liu and Fearn, 1993 and 2000; Lane et al., 2011) and along the North Atlantic coast from South Carolina (e.g. Hippensteel and Martin, 1999; Scott et al., 2003) to New

Jersey and New England (e.g. Donnelly et al., 2001; and 2004). In addition, records from Belize (McCloskey and Keller, 2009; Denommee et al., 2014), Puerto Rico (Donnelly and Woodruff, 2007; Woodruff et al., 2008) and the Bahamas (Park, 2012) exist. These studies indicate that the frequency of hurricane landfalls in these regions has varied on centennial to millennial scales and that the position of the polar jet stream and the Bermuda-Azores High, variations in ENSO and the African Monsoon, and SSTs likely have long-term effects on hurricane landfalls. More recently, the assembly of paleotempestological research from multiple North Atlantic basin sites affirms an ENSO link and a connection to tropical North Atlantic warmth (Mann et al., 2009).

These pioneering studies have yielded important information on long-term hurricane dynamics. However, the records are confined to a few geographical locations. To date, no well-established paleo-hurricane records exist for the densely populated Southwest Florida coast, even though this area is a prominent hurricane target zone with a return period of 7-8 years for hurricane-strength storms (Neumann, 1991). To address this issue, we use the paleotempestology proxies of grain size, percent CaCO₃, and shell species from Southwest Florida lagoonal sediment cores to reconstruct 1000 years of hurricane history.

2. Material and Methods

2.1. Site Description and Field Work

Our study site, Island Bay, is located behind Keewaydin Island in Southwest Florida (Fig. 1). Keewaydin Island, located northwest of the Ten Thousand Islands and Everglades National Park, is one of many barrier islands that extend along Florida's west coast (Yale, 1997) and forms the outermost barrier of the Rookery Bay National Estuarine Research

119 Reserve. The age of this barrier island is unknown, though the southern end of the island has a
120 complex history dating back at least 3,000 years (Barthle & Savarese, 2009), and other barrier
121 islands in the area have been dated to approximately 2,700 yrs. BP. (Savarese et al., 2004;
122 Wohlpert et al., 2007). Island Bay is one of the many tidally influenced, brackish back-barrier
123 lagoons protected by Keewaydin Island. The lagoon is connected to the eastern inner-coastal
124 waterway via narrow mangrove-lined tidal channels, which transport very fine- to fine-
125 grained sands and silts ($<250\ \mu\text{m}$). Storm surge into the lagoon via these channels is not likely
126 to occur given the protective nature of the site and low tidal regime. In this calm, protected
127 region behind the barrier, organic rich, soft-sand bottoms are dominant, with occasional oyster
128 beds (*Crassostrea virginica*) that occur marginally. However, little evidence of prolific oyster
129 reefs exist in Island Bay. In addition, very limited bivalve, gastropod, mollusk, and crustacean
130 growth exist within the lagoon.

Figure 1. A) State of Florida, U.S.A. highlighting Keewaydin Island B) Keewaydin Island along the Southwest Florida coastline highlighting Island Bay C) Island Bay located on Keewaydin Island's northern end in Southwest Florida displaying location of cores 1206-22 (22) and 1206-23 (23).

Two coring locations within Island Bay were marked by GPS (Fig. 1). Cores were taken at these locations by hand-coring technique, using an aluminum pipe of three-inch diameter and detachable handles. To account for sediment compaction, the height of the sediment outside the pipe was subtracted from that on the inside of the pipe. The sediment core was then extracted by filling the remainder of the pipe with water and then sealing the pipe to create a vacuum. Extra pipe was cut from the top of the core and the core was re-capped before transportation. Cores were taken back to the Florida Gulf Coast University (FGCU) sedimentary laboratory and split for analysis. Using a Trimble RTK unit, model 8A, a beach profile was obtained seaward of the bay across the barrier island to determine the relative vulnerability of the site to storm overwash (Fig. 2). The elevation of the core sediment surfaces relative to mean high water was also obtained and calibrated against NAVD88 using a surveyed landmark.

Figure 2. Island width profile and elevation relative to mean sea level [North American Vertical Datum, 1988 (Zilkoski et al., 1992)] taken seaward of Island Bay.

2.2. Radiometric Dating

Our sediment core chronology relies on both ^{210}Pb and ^{14}C radiometric dating techniques. Bulk samples were taken at intervals ranging from 1 to 7 cm in the uppermost 25 cm of core 1206-22 (Table 1). These sediments were analyzed for ^{210}Pb activity using a GAM-AN1F Germanium Detector. The ^{210}Pb age model is based on a constant rate of supply (CRS) model (Binford, 1990).

For the remainder of core 1206-22, available plant and wood fragments were collected, cleaned, dried, and sent to Beta Analytic, Miami, for radiocarbon dating. Three radiocarbon dates were obtained for core 1206-22 and one for core 1206-23 (Table 1). Calibration curves from the Calib7 program with IntCal13 and MARINE13 data sets were used to calculate ^{14}C calendar ages (in years before present, where present is 1950 A.D. by convention) and corresponding uncertainties (Reimer et al., 2013).

TABLE 1. ^{210}Pb AND RADIOCARBON DATES FROM CORE 1206-22, KEEWAYDIN ISLAND, FLORIDA

Core	Sample Depth (cm)	Material	Excess ^{210}Pb			CRS Ages		
1206-22	0.5	Bulk peat	0.75	+/-	0.09	2011	+/-	3.11
1206-22	2	Bulk peat	1.35	+/-	0.11	2009	+/-	3.07
1206-22	2.5	Bulk peat	0.99	+/-	0.10	2006	+/-	3.05
1206-22	5.5	Bulk peat	1.22	+/-	0.05	1998	+/-	2.91
1206-22	7.5	Bulk peat	1.08	+/-	0.04	1990	+/-	2.77
1206-22	14.5	Bulk peat	0.58	+/-	0.08	1949	+/-	4.14
1206-22	15.5	Bulk peat	0.72	+/-	0.05	1938	+/-	7.31
1206-22	16.5	Bulk peat	0.12	+/-	0.03	1930	+/-	11.28
1206-22	20.5	Bulk peat	0.25	+/-	0.05	1900	+/-	53.66
1206-22	21.5	Bulk peat	0.21	+/-	0.07	1880	+/-	119.31
1206-22	22.5	Bulk peat	0.18	+/-	0.07	1855	+/-	184.97
Core	Sample Depth (cm)	Material	Measured Radiocarbon Age (yrs BP)			Calibrated Age (yrs BP)		
1206-22	46.5	Wood	330	+/-	30	385	+/-	30
1206-22	94.5	Shell	650	+/-	30	575	+/-	30
1206-22	152.5	Wood	890	+/-	30	740	+/-	30
1206-23	196.5	Wood	1040	+/-	30	860	+/-	30

2.3. Sediment and Paleontological Analyses

Grain size analyses were performed on samples taken every 2 cm throughout the entire length of cores 1206-22 and 1206-23, and with 1 cm resolution through suspected paleotempestite layers. Samples 1 cm³ in size were extracted from each core, dried and weighed, and then wet sieved using a 2 mm sieve and deionized water, and then placed in a drying oven at 105°C overnight. Dried sieve samples were then weighed and used to determine percentage by volume of sediment coarser than 2 mm, thereby identifying peaks in “gravel” grain size.

Bulk CaCO₃ was measured on a UIC, Inc. model CM-5015 Calcium Carbonate Coulometer at the FGCU (uncertainties were <2%). Representative samples were taken at 5 cm intervals throughout cores 1206-22 and 1206-23 and at 1 cm resolution through suspected paleotempestites. Bulk CaCO₃ concentrations in core samples are the product of shell gravels and carbonate mud, both with marine sources seaward of the barrier island. The use of bulk calcium carbonate is a supporting proxy to the grain size analysis, as paleotempestite layers are generally composed of larger grain-sized shell material. Treated as such, elevated levels of CaCO₃ alone do not define a paleotempestite but rather provide supporting evidence of overwash to those layers defined by grain size.

The presence of offshore and nearshore marine mollusk species in coastal back-barrier lagoonal sediments is also a useful indicator of marine overwash (Liu and Fearn, 2000). Therefore, we identified the death assemblage of molluscan species within the paleotempestite layers. Shells were categorized based on life habitat: estuarine; estuarine and marine; and marine. Those species with strict marine lifestyles are of most interest as they indicate overwash and displacement of marine shells into the back-barrier setting. Diagnostic taxa used in this study to confirm the marine origin of shells or shell fragments found within

the paleotempestites include *Chione cancellata* (cross-barred Venus clam) (Abbot, 1974), *Anomia simplex* (jingle shell) (Gosner, 1978), *Vermetus nigricans* (vermetid gastropod) (Vaught, 1989), and *Gemophos tinctus* (tinted Cantharus) (Rosenberg et al., 2009). These shells were identified as marine species in the literature and provide further evidence that embedded shell layers are the likely product of hurricane overwash originating from the marine foreshore and offshore environments. However, due to shell fragmentation it was difficult to identify marine shell species within a few of the tempestite layers.

2.4 Grain Size Statistical Analyses

In order to define the total number of paleotempestites within cores 1206-22 and 1206-23, a background sediment grain-size was calculated. We first identified the extreme outliers (points that fall outside of the upper quartile) using a box plot quartile analysis. These outliers were excluded from the two datasets and the mean and standard deviations were re-calculated. The background was then defined by the newly calculated mean and considered a grain size measurement greater than 2 standard deviations from this mean to be a storm event (Barnett and Lewis, 1994)(Fig. 2). These values were calculated as 4.44% and 7.76% gravel, for cores 1206-22 and 1206-23 respectively.

3. Results and Discussion

3.1 Key Beds as Paleotempestites

Low energy back-barrier lagoons and bays have significantly different sedimentology than that of high energy, wave-influenced beaches and bars (Stapor et al., 1991). Typically, back-barrier lagoons consist of fine-grained, organic-rich sediments, and in most cases the presence of coarse-grained sediments is attributed to short-lived, high-energy, storm-induced

conditions (Boggs, 1995). The sedimentology of Island Bay consists mostly of sands and silts (<0.5 mm) with some organic material. The lack of an obvious freshwater drainage system neighboring the lagoon suggests that runoff does not play a major role in sediment deposition; sediments in Island Bay must have a tidal or marine overwash origin. Throughout cores 1206-22 and 1206-23 multiple shell hash layers (grain size >2 mm) are interbedded within the sand and silt background sediment. Through the use of paleotempestologic proxies, this study establishes that these layers are the remnants of discrete overwash events, triggered by intense hurricane storm surge. In addition, both cores display a coarse-grained sand layer (grain-size >1 mm) close to the top of the core, which is also interpreted as a hurricane surge-driven paleotempestite. Other paleotempestology studies (e.g. Liu and Fearn, 1993; Donnelly et al., 2001; and Donnelly, 2005) have documented similar thin-bed sand layers resulting from overwash deposition. The layers are visually distinct, but we used grain size analysis, percent calcium carbonate, and marine mollusk species identification to better differentiate the paleotempestites from the background lagoonal sediment.

Cores 1206-22 and 1206-23 have relatively consistent sedimentation rates throughout the cores (with a mean of 0.27 cm yr⁻¹ and 0.23 cm yr⁻¹ respectively) and no bioturbation was noted in either core. Additionally, no lamination or ichnofabric (structures produced by organismal activity) was observed in either core. Based on grain size data, 15 paleotempestites (T₁–T₁₅) were identified in core 1206-22, occurring at the following stratigraphic positions: 9 cm (T₁); 20 cm (T₂); 70 cm (T₃); 74 cm (T₄); 82 cm (T₅); 97 cm (T₆); 108 cm (T₇); 113 cm (T₈); 128 cm (T₉); 161 cm (T₁₀); 170 cm (T₁₁); 196 cm (T₁₂); 207 cm (T₁₃); 222 cm (T₁₄); and, 225 cm (T₁₅). In Figure 3, these storm layers are depicted as peaks in % coarse of dry weight that exceed the vertical dotted line, which delineates storm

events from the average background sedimentation. All layers, with the exception of T₂, consist of broken shell material, the majority of which are marine gastropods and others that resemble a foreshore or nearshore assemblage. T₂ is a thin coarse-grained quartz sand bed, approximately 1 cm in thickness, with small amounts of embedded shell hash. Although T₂ is the only sand layer in the core, there are other paleotempestites as well that do not contain identifiable shell species.

Eleven paleotempestites (T₁ – T₁₁) were detected in core 1206-23 (Fig. 3) based on grain size, with the following stratigraphic positions: 14 cm (T₁); 17 cm (T₂); 40 cm (T₃); 40 cm (T₄); 120 cm (T₅); 137 cm (T₆); 139 cm (T₇); 179 cm (T₈); 214 cm (T₉); 216 cm (T₁₀); and, 229 cm (T₁₁). All layers, with the exception of T₁, consist of similar offshore or nearshore material as described in core 1206-22. T₁, similar in the composition to T₂ in core 1206-22, consists of white coarse-grained sand with small amounts of embedded shell hash, while the composition of T₂ in core 1206-23 resembles that of T₁ in core 1206-22. The different compositions of these layers is likely evidence that a given storm surge does not deposit the same material uniformly in back-barrier locations, but rather that the deposition of tempestites is influenced by geomorphology, vulnerability, and depositional characteristics of the specific location. This non-uniform distribution of deposit material, consisting of both coarse sand and broken shells, might also explain why the paleotempestites in both cores do not strongly correlate with depth. It is likely that the local bathymetry within the lagoon varies from point to point as well as the depositional regime at each location even on a scale of 20 meters (distance between cores). The pattern of storm deposition between cores is similar however direct layer correlation is not possible for a large portion of the cores. In addition, the poor correlation between paleotempestites among cores is also compounded by the lack of ¹⁴C age

251 control points in core 1206-23. With only one ^{14}C date obtained, a reliable age model for core
 252 1206-23 could not be generated and therefore storm deposit comparisons based on age rather
 253 than depth was not performed. However, using the one ^{14}C date to create a preliminary age
 254 model does yield a much higher correlation between storm layers in each core.

Figure 3. Stratigraphic columns and grain size profiles of cores 1206-22 and 1206-23. The horizontal dotted line identifies storms in the modern record (<150 yrs. BP). The vertical dotted line delineates the average background signal (+2 σ from mean) from storm events in each core.

255

256 *3.2 Island Bay Age Control*

The atmospheric-deposited amount of excess lead ($^{210}\text{Pb}_{\text{exc}}$) was used to provide age assessment in the top 23 centimeters of core 1206-22 (Table 1). Eleven $^{210}\text{Pb}_{\text{exc}}$ ages were derived from the sediment above this depth that range from *ca.* 1855 to *ca.* 2011. The Binford algorithm used to calculate sample ages assumes equilibrium ($^{210}\text{Pb}_{\text{exc}} = 0$) at the bottom of the core, thereby assuming the age of the bottom to be infinite. As such, the algorithm tries to fit all data into this scenario, producing extremely old ages in the last samples. According to Table 1, the calculated sedimentation rate for the most recent sediment (0-23 cm) is 0.25 cm yr⁻¹.

Age control points were taken throughout cores 1206-22 and 1206-23 to construct the age model used to date the cores (Fig. 3). Three radiocarbon dates provided age control for core 1206-22 and are used to calculate an average mean sedimentation rate of 0.27 cm yr⁻¹, placing the bottom (228 cm) of core 1206-22 at 954 yrs. BP. Core 1206-23 contains one radiocarbon date at 196 cm that returned a calibrated age of 860 yrs. BP. This date was used to construct an average sedimentation rate of 0.23 cm yr⁻¹ and also to estimate the age of the deepest part of the core (234 cm) at approximately 1026 yrs. BP. The lack of radiocarbon datable material through the cores prevented any supplemental age control.

3.3 Modern Record of Southwest Florida Hurricane Dynamics

Grain size (>2 mm) and calcium carbonate (ranging from 0–4%) analyses defined two paleotempestites (T₁ and T₂) in the top 24 centimeters of cores 1206-22 and 1206-23. These results were supported by the identifiable marine species (e.g. *Chione cancellata*, *Anomia simplex*, *Vermetus nigricans*, and *Gemophos tinctus*) found within the paleotempestites. These events are of particular interest because they have occurred in the last 150 years and can

280 therefore be correlated with the historical hurricane record (Table 2). In core 1206-22 the
281 ^{210}Pb dating constrained T_1 between *ca.* 1949 ± 3 YR and 1990 ± 3 YR. During this time, the
282 only hurricane causing significant storm surge in Southwest Florida was Hurricane Donna in
283 1960, with a reported storm surge height of 3.11 m in the city of Naples (Barnes, 2007). The
284 height of the modern dune between Island Bay and the foreshore is approximately 1.60 m
285 above sea level relative to NAVD88 (Fig. 2). If we assume a similar dune structure in 1960,
286 the 3.11 m storm surge generated from Hurricane Donna would have breached the dune and
287 have extended well into the back-barrier lagoon. This layer, which was deposited at
288 approximately 9-14 cm depth, appears in all cores taken at this site. ^{210}Pb -dating analyses
289 conclude that Hurricane Donna is most likely represented by the uppermost tempestite layer
290 in Island Bay. For this reason, an age of 1960 was applied to T_1 in core 1206-23, despite the
291 absence of ^{210}Pb dating for this core.

292 In core 1206-22, T_2 was dated between *ca.* 1900 ± 54 YR and *ca.* 1930 ± 11 YR. Due
293 to the wider ^{210}Pb dating age interval on this paleotempestite, there are three possible storms
294 that may have deposited the T_2 storm layer: the Great Miami Hurricane of 1926, the Un-
295 named Hurricane of 1910, and the Un-named Hurricane of 1873 (Table 2). The storm surge
296 associated with the 1926 Miami Hurricane was reported to be 2.44 m in nearby Everglades
297 City (located ~40 miles south of Keewaydin Island) with a category 4 status (McDonald,
298 1935), while the 1910 storm, possibly the most destructive storm to hit Southwest Florida
299 before Hurricane Donna, made landfall near Cape Romano (located ~20 miles south of
300 Keewaydin Island) as a strong category 3 and was reported to have flooded a 2.74 m above
301 sea level home in Everglades City (Landsea et al., 2003). This storm in the historical record
302 also destroyed the historic Naples Pier (located ~10 miles north of Keewaydin Island).

Preceding this storm, an un-named hurricane in 1873 made landfall in Fort Myers with a storm surge of 4.26 m at Punta Rassa. The Labor Day Hurricane of 1935 is also a potential candidate, but due to its relatively small size and offshore track, it is unlikely that the maximum surge height of 1.8 m was observed on Keewaydin Island. Without further evidence or more precise dating, the T₂ layer may be the result of any of these three storms. However, the Great Miami Hurricane first made landfall on the east coast of Florida and then crossed the state before making landfall in Naples, whereas both the 1873 and 1910 storms were direct land-falling storms with greater storm surges, making back-barrier deposition more likely.

TABLE 2. STORM SURGE (RELATIVE TO MEAN HIGH SEA LEVEL) AND ATMOSPHERIC DATA OF KNOWN STORMS IN SOUTHWEST FLORIDA (Landsea et al., 2003)

Year	Major Storms	Category	Surge Height (meters)	Surge Location	Max Wind Speed (mph)	Radius of Max Winds (nautical miles)
2005	Wilma	3	2.13	Marco Island	175	26
2004	Charley	4	2.74	Sanibel Island	150	6.9
1992	Andrew	4	1.81-2.11	Everglades City	172	11
1960	Donna	4	3.11	Naples	121	18
1935	Labor Day	5	1.84	Naples	185	22
1926	Great Miami	4	2.44	Everglades City	128	20
1910	Not named	3	3.65	Punta Rassa	126	28
1873	Not Named	3	4.26	Punta Rassa	115	26

What is evident from the Island Bay upper-most sediments is that not all hurricanes coming within 74 kilometers of Island Bay are being recorded as paleotempestites. Our historical hurricane record for this site (Table 2) includes storms of category 3-5 strength. Of the eight hurricanes listed as category 3-5, only two storms are represented as paleotempestites in the sediment cores taken at this location. Interestingly, the ²¹⁰Pb dating indicates that these modern paleotempestites (T₁ and T₂) are deposited by large radius, significant storm surges produced by category 3-5 hurricanes. The lack of congruency

319 between the historical and geological records is an issue that has been discussed in other
320 paleotempestology studies (Park, 2012; Hippensteel et al., 2013; van Hengstum et al., 2014)
321 and continues to be of interest. Several factors may contribute to the lack of paleotempestite
322 deposition in Island Bay including geomorphology of the site, general susceptibility to
323 overwash and storm dynamics. Geomorphology includes factors such as dune height, distance
324 from the foreshore, and site orientation relative to the coast. Dune height must be considered
325 in concert with storm surge when anticipating paleotempestite deposition. Since historic dune
326 heights are largely unknown, only estimates can be assumed. Nonetheless, coastal regions do
327 exhibit consistent patterns in dune height. The mean dune height of a region could serve as a
328 storm's minimal surge threshold for potential overwash. In our case, overwash is only likely
329 to occur with a combination of storm surge and waves greater than 1.6 m, which is the current
330 dune height. Since this height is relative to others in Southwest Florida, it is assumed that the
331 dune height was similar in the recent past. We are assuming, therefore, that older
332 paleotempestites (T₃ or older) must also represent storm surge heights of nearly 2 m and that
333 Island Bay is only recording the history of intense hurricanes. Hence the geomorphology and
334 particularly dune height affect the relative vulnerability of the site to storm overwash. Another
335 factor, which is less understood, is how storm dynamics affect overwash processes and
336 paleotempestite deposition. Direct landfall hurricanes for example generally produce more
337 overwash than those that sweep the coast or come from behind and travel across land (Paxton,
338 unpublished). Accordingly, not every storm within the proximity to a coastline will deposit
339 sediment in back-barrier locations. A combination of coastal and site geomorphology, storm
340 dynamics, and general susceptibility to overwash may help to explain inconsistencies between
341 historic and geologic records.

3.4. Long-term Record of Southwest Florida Hurricane Dynamics

Our paleotempestology record displays approximately 1,000 years of intense hurricane-related overwash in Island Bay (Fig. 4). Geologic proxies (e.g. grain size, % CaCO_3 , and mollusk identification) of the paleotempestite layers support inactive and active periods within our record. During the most recent 500 years of the record (500 yrs. BP – 0), 3–4 major storms were recorded at the Island Bay core site. The period from 500-150 yrs. BP is referred to as the “inactive” or calm period, in which only 1-2 paleo-tempestites were recorded in either core. In earlier years (1000 yrs. BP – 500 yrs. BP), 7–11 major storms were recorded in cores 1206-22 and 1206-23. This is referred to as the “active” period in the record. These inactive and active periods correspond with various global temperature anomaly reconstructions that define the Little Ice Age (LIA)(500-150 yrs. BP) and Medieval Warm Period (MWP) (1000-500 yrs. BP) in our record, respectively. The black box in Figure 4 highlights the active period in our record while the gray box highlights the inactive period.

Figure 4. Grain size (in % coarse of dry weight >2 mm) (black) and calcium carbonate (gray) profiles of cores 1206-22 and 1206-23. The dotted line delineates storm events from the background sedimentation in each core. The black box highlights the “active” period in the record from 1000 – 500 yrs. BP that corresponds to the Medieval Warm Period (MWP). The grey box highlights the inactive period (500-150 yrs. BP) which corresponds to the Little Ice Age (LIA). The most recent years (150 yrs. BP to present) do not correlate with either period.

3.5. Comparisons with Other Paleotempestology Records

In order to assess the validity of our record and to identify potential large-scale climate drivers, our record was compared with multiple paleotempestology records from both the Gulf of Mexico (GoM) and the Caribbean regions (Fig. 5). The Denommee et al. (2014) record (Fig. 5C) from Belize shows many similarities to our record, with a more active period of intense hurricane landfalls observed between 1200-650 yrs. BP, beginning approximately 150 years before ours. Again, similar to our record, a calm period is identified between 600-100 yrs. BP. Lane et al. (2011) (Fig. 5B) published a record from a sinkhole in Northern Florida that also shows many of the same similarities to our Southwest Florida record and the Denommee et al. (2014) record. Although the Lane et al. (2011) record spans 5,000 years (not shown in its entirety), the first 1,000 years indicate a similar intense hurricane landfall pattern to that of our record, with an active period from about 1,000 yrs. BP – 500 yrs. BP and an inactive period between 500-150 yrs. BP. This North Florida record (Lane et al. 2011), in terms of number of high-threshold storms per century, peaks at 700 yrs. BP, which is similar to Denommee et al. (2014). Both records place the peak of their active period approximately 50 years earlier than ours (750-650 yrs vs. 700-600 yrs). This age gap may be the result of radiometric dating discrepancies or due to the lack of intense hurricane landfalls in Southwest Florida during that time, rather than a shift in climate. The shaded box in Figure 5 shows the similarities among the records.

Figure 5. Comparison to other paleotempestology and climate records. A) Southwest Florida (*this study*) B) Lane et al. (2011), northern Florida C) Denommee et al. (2014), Belize D) Mann et al. 2009, SST Reconstruction MDR North Atlantic. (B) HT refers to “high threshold” meaning those storms that generated a deposit at least as coarse as the strongest historic storm to hit the field site. (C) TC events include tropical storms to major hurricanes, not exclusively intense hurricanes. The grey box identifies similarities among the records.

Other records from the GoM (Liu and Fearn, 1993; Horton et al., 2009), Puerto Rico (Donnelly, 2005; Donnelly et al., 2007), and the Bahamas (Park, 2012) do not correlate as well to the Southwest Florida record. These results indicate that the climate forcings that have controlled intense hurricane landfalls in these locations may be different from those along the Florida Gulf Coast, including Southwest Florida and Apalachee (Lane et al., 2011), and Belize (Denommee et al. 2014) during the last 1,000 years.

3.6. Long-term Hurricane Climate Drivers

The most likely long-term hurricane climate drivers for Southwest Florida hurricane variability are ENSO (Moy et al., 2002) and elevated SSTs (Mann et al., 2009). Our record from Island Bay best correlates with MDR SSTs, which shows an increase in SSTs over the past 150 years, preceded by a decrease in SSTs for 350 years, and preceded again by slightly warmer SSTs from 1000 yrs. BP – 500 yrs. BP (Fig. 5D). These SSTs correspond with recent warming, cooling associated with the LIA, and warming associated with the MWP. Peaks in SSTs during the MWP coincide with increased overwash deposits in our Southwest Florida paleotempestology record, while the LIA (500-150 yrs. BP) SST reconstructions correlate with no statistically significant overwash layers. These correlations are in agreement with the literature that demonstrates an increase in SSTs results in more frequent, intense hurricane activity (Emanuel, 2005; Elsner et al., 2006; Emanuel, 2007; Holland and Webster, 2007; Saunders and Lea, 2008).

SSTs in the GoM (Richey et al., 2007) display a different pattern over the past 1,200 years than that of the MDR in the North Atlantic. Paleotempestology records that correlate with this record are more likely to be found along the northwestern GoM coastline, as hurricanes that make landfall in that region track in the GoM before making landfall. This may explain why our record looks different from that of Liu and Fearn (1993; 2000), and Horton et al. (2009). Hurricane landfalls in Southwest Florida seem to be more influenced by MDR SSTs (Mann et al., 2009). This is intuitive since the majority of modern hurricanes making landfall in Southwest Florida form in the MDR and track across the North Atlantic before making landfall in Southwest Florida. The active and calm patterns observed in our record do not correlate well with an ENSO-Ecuador record (Moy et al., 2002) which indicates a distinct pattern of less intense ENSO events over the past 500 years, followed by a much

stronger ENSO signal from 1,100 yrs. BP – 500 yrs. BP. This record, according to Donnelly and Woodruff (2007), should produce the opposite pattern of hurricane landfalls in Southwest Florida. Conditions indicative of Normal or La Niña conditions should encourage hurricane formation and those indicative of El Niño conditions are responsible for fewer hurricanes due to the expected higher incidence of wind shear. However, even though the mean seasonal shear is increased during El Niño conditions, there are still short periods of favorable conditions within such a season due to other effects that may lead to the formation of a hurricane (e.g. Hurricane Andrew, 1992).

4. Conclusions

Using proxy tests and radiometric dating, we present a 1,000-year-long intense hurricane landfall record for Southwest Florida. The proxies indicate two paleotempestite layers (T_1 and T_2), dated by ^{210}Pb analysis, within the last 150 years. The upper paleotempestite has been identified as Hurricane Donna (1960), whereas the older paleotempestite could represent the un-named Hurricane of 1873, the un-named Hurricane of 1910, or the Great Miami Hurricane of 1926. The short-term record from Island Bay indicates that only intense hurricanes (category 3-5) with significant storm surge leave overwash at this site. The long-term trends in our Southwest Florida hurricane record resemble hurricane records from Northern Florida (Lane et al., 2011) and Belize (Denommee et al., 2014). An active (inactive) period was identified between 1000 - 500 (500 - 150) yrs. BP. in all three studies. This may indicate the influence of the same large-scale climate driver at all sites. Our initial assessment for Southwest Florida indicates that SSTs in the MDR are a potential major driver for intense hurricane landfalls along the Southwest Florida coast. Both cores 1206-22

and 1206-23 are positively correlated with reconstructed North Atlantic SSTs for the MDR (Mann et al., 2009). Here, warmer SSTs between 1000 – 500 yrs. BP (MWP) are correlated with an active **intense** hurricane period, while cooler SSTs between 500 – 150 yr. BP (LIA) correspond to an inactive or calm **intense** hurricane period. ENSO does not appear to be the dominant long-term driver for intense hurricane activity in Southwest Florida over the last one thousand years as our record is in opposition to established ENSO-hurricane trends. **Future paleotempestologic studies in Southwest Florida, and those in other key hurricane prone regions, will be essential for strengthening the understudied relationship between long-term intense hurricane landfalls and climatic driving forces.**

Acknowledgments

Funding for this project was provided by the National Science Foundation (OCE-1335375; OCE-1335207) and Florida Seagrant. Field assistance was provided by the Rookery Bay National Estuarine Research Reserve and students from Florida Gulf Coast University. Laboratory analyses were aided by the geology and chemistry departments at Florida Gulf Coast University.

References

- Abbot, R.T. 1974. American Seashells, The Marine Mollusca of the Atlantic and Pacific Coasts of North America. Second edition. Van Nostrand Reinhold Company, New York, pp. 663.
- Barnes, J. Florida's Hurricane History. The University of North Carolina Press, North Carolina. 2007.
- Barnett, V. and Lewis, T. 1994. "Outliers in Statistical Data", 3rd Edition. John Wiley and Sons.

- Barthle, J. and Savarese, M. 2009. Reconstructing former Southwest Florida's barrier island down-core history from the distribution of estuarine and open shelf facies, *Geol. Soc. of Am. Abst. with Programs*, Vol. 41, No.1, pp. 50.
- Binford, M.W. 1990. Calculation and uncertainty analysis of ^{210}Pb dates for PIRLA project lake sediment cores, *J. Paleolimnology*, Vol. 3, pp. 253-267.
- Boggs Jr., S. Principles of Sedimentology and Stratigraphy. New Jersey: Prentice Hall, 1995.
- Bove, M.C., Elsner, J.B., Landsea, C.W., Niu, X., and O'Brien, J.J. 1998. Effect of El Niño on U.S. Landfalling Hurricanes, Revisited. *Bull. Amer. Meteor. Soc.*, No. 79, Vol. 11, pp. 2477-2482.
- Collins, J.M., and Mason, I.M. 2000. Local environmental conditions related to seasonal tropical cyclone activity in the Northeast Pacific basin, *Geophys. Res. Lett.*, Vol. 7, Issue 23, pp. 3881-3884.
- Denommee, K.C., Bentley, S.J., and Droxler, W. 2014. Climate controls on hurricane patterns: a 1200-y near-annual record from Lighthouse Reef, Belize, *Scientific Reports*, Vol. 4, article no. 3876.
- Donnelly, J.P. and Woodruff, J.D., 2007. Intense hurricane activity over the past 5,000 years controlled by El Niño and the West African monsoon, *Nature*, Vol. 447, pp. 465-468.
- Donnelly, J.P. 2005. Evidence of past intense tropical cyclones from backbarrier salt pond sediments: A case study from Isla de Culebrita, Puerto Rico, USA, *J. Coast. Res., SI*, Vol. 42, pp. 201-210.
- Donnelly, J.P., Butler, J., Roll, S., Wengren, M., and Webb III, T. 2004. A backbarrier overwash record of intense storms from Brigantine, New Jersey, *Mar. Geol.*, Vol. 210, pp. 107-121.
- Donnelly, J.P., Roll, S., Wengren, M., Butler, J., Lederer, R., and Webb III, T. 2001. Sedimentary evidence of intense hurricane strikes from New Jersey, *Geology*, Vol. 29, pp. 615-618.
- Elsner, J.B. and Kara, A. B., 1999. Hurricanes of the North Atlantic: Climate and Society. Oxford: Oxford University Press.
- Elsner, J.B., Kossin, J.P., and Jagger, T.H. 2008. The increasing intensity of the strongest tropical cyclones, *Nature*, Vol. 455, pp. 92-95.
- Elsner, J.B. 2006. Evidence in support of the climate change: Atlantic hurricane hypothesis, *Geophys. Res. Lett.*, Vol. 33, L16705.

- 501 Elsner, J.B. 2007. Tempestites in time. *Nature*, Vol. 447. pp. 647-649.
- 502
- 503 Emanuel, K. 2007. Comment on “Sea-surface temperatures and tropical cyclones in the
504 Atlantic basin” by Patrick J. Michaels, Paul C. Knappenberger, and Robert E. Davis,
505 *Geophys. Res. Lett.*, Vol. 34, L06702.
- 506
- 507 Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years,
508 *Nature*, Vol. 436, pp. 686–688.
- 509
- 510 Emanuel, K.A., Sundararajan, R., and Williams, J. 2008. Hurricanes and global warming:
511 Results from downscaling IPCC AR4 simulations, *Bull. Am. Meteorol. Soc.*, Vol. 89,
512 pp. 347-367.
- 513
- 514 Goldenberg, S.B., and Shapiro, L.J. 1996. Physical mechanisms for the association of El Niño
515 and West African rainfall with Atlantic major hurricanes, *J. Clim.*, Vol. 9, pp. 1169–
516 1187.
- 517
- 518 Goldenberg, S.B., Landsea, C.W., Mestas-Nunez, A.M., and Gray, W.M. 2001. The recent
519 increase in Atlantic hurricane activity: Causes and implications, *Science*, Vol. 293, pp.
520 474–479.
- 521
- 522 Gosner, K.L. 1978. A Field Guide to the Atlantic Seashore. Houghton Mifflin, Boston.
- 523
- 524 Gray, W.M. 1984. Atlantic seasonal hurricane frequency, Part I: El Niño and 30-mb quasi-
525 biennial oscillation influences, *Mon. Wea. Rev.*, Vol. 112, pp. 1649–1668.
- 526
- 527 Gray, W. and Sheaffer, J. 1991. El Niño and QBO influences on tropical cyclone activity, in:
528 Glantz, M., Katz, R. and Nicholls, N. (Eds.), *Teleconnections Linking World Wide*
529 *Climate Anomalies*, Cambridge University Press.
- 530
- 531 Hippensteel, S.P. and Martin, R.E. 1999. Foraminifera as an indicator of overwash deposits,
532 barrier island sediment supply, and barrier island evolution, Folly Island, South
533 Carolina, *Palaeogeogr., Palaeocl.*, Vol. 149, pp. 115–125.
- 534
- 535 Hippensteel, S.P., Eastin, M.D. and Garcia, W.J. 2013. The geological legacy of Hurricane
536 Irene: Implications for the fidelity of the paleo-storm record, *GSA Today*, Vol. 23, No.
537 12, pp. 4-10.
- 538
- 539 Holland, G.J., and Webster, P.J. 2007. Heightened tropical cyclone activity in the North
540 Atlantic: Natural variability or climate trend, *Philos. Trans. R. Soc. London*, Ser. A.
- 541
- 542 Horton, B.P., Rossi, V., and Hawkes, A.D. 2009. The sedimentary record of the 2005
543 hurricane season from the Mississippi and Alabama coastlines, *Quat. Int.*, Vol. 195,
544 pp. 15-30.
- 545

- Knaff, J.A., 1997. Implications of summertime sea level pressure anomalies in the tropical Atlantic region, *J. Clim.*, Vol. 10, pp. 789–804.
- Landsea, C.W., Pielke Jr., R.A., Maestas-Nunez, A.M., and Knaff, J.A. 1999. Atlantic basin hurricanes, *Clim. Change*, Vol. 42, pp. 89–129.
- Landsea, C.W., Anderson, C., Charles, N., Clark, G., Dunion, J., Fernandez-Partagas, J., Hunderford, P., Neumann, C., and Zimmer, M. 2003. The Atlantic hurricane database re-analysis project results for the first 60 years – 1851 to 1910, 14th Symposium on Global Climate Change and Climate Variations, Long Beach, CA 9-13 February, 2013.
- Landsea, C.W., Hagen, A., Bredemeyer, W., Carrasco, C., Glenn, D.A., Santiago, A., Strahan-Sakoskie, D., and Dickinson, M. 2013. A Reanalysis of the 1931–43 Atlantic Hurricane Database*, *J. Clim.*, Vol. 27, pp. 6093-6118.
- Lane, P., Donnelly, J.P., Woodruff, J.D., and Hawkes, A.D. 2011. A decadal-resolved paleohurricane record archived in the late-Holocene sediments of a Florida sinkhole, *Mar. Geol.*, Vol. 287, pp. 14–30.
- Liu, K.B., and Fearn, M.L. 1993. Lake-sediment record of late Holocene hurricane activities from coastal Alabama. *Geology*, Vol. 21, pp. 793–796.
- Liu, K.B., and Fearn, M.L. 2000. Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records, *Quat. Res.*, Vol. 54, No. 2, pp. 238-245.
- Lupo, A.R., Latham, T.K., Magill, T., Clark, J.V., Melick, C.J., and Market, P.S. 2008. The interannual variability of hurricane activity in the Atlantic and East Pacific Regions, *Nat. Wea. Dig.*, Vol. 32, No. 2, pp. 119-135.
- Mann, M.E., Woodruff, J.D., Donnelly, J.P., and Zhang, Z. 2009. Atlantic hurricanes and climate over the past 1500 years, *Nature*, Vol. 460, pp. 880–885.
- McCloskey, T.A. and Keller, G. 2009. 5000 year sedimentary record of hurricane strikes on the central coast of Belize, *Quat. Int.*, Vol. 195, Issue 1, pp. 53-68.
- Mendelsohn, R. and Saher, G. 2011. The global impact of climate change on extreme events. World Bank Washington, DC.
- McDonald, W.F. 1935. The hurricane of August 31 to September 6, 1935, *Mon. Wea. Rev.*, Vol. 63, pp. 269-271.
- Moy, C.M., Seltzer, G.O. Rodbell, D.T. and D.M. Anderson. 2002. Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch, *Nature*, Vol. 420, pp. 162–165.

- Malmstadt, J., Scheitlin, K., and Elsner, J. 2009. Florida hurricanes and damage costs. *Southern Geograph.*, Vol. 49, Issue 2, pp. 108-131.
- Neumann, C.J. 1991. The National Hurricane Center Risk Analysis Program (HURISK), NOAA Technical Memorandum NWS NHC 38, National Oceanic and Atmospheric Administration (NOAA), Washington, DC, 1991.
- Nordhaus, W. 2010. The Economics of Hurricanes and Implications of Global Warming, *Clim. Change Econ.*, Vol. 1, pp. 1-24.
- O'Brien, J.J., Richards, T.S., and Davis, A.C. 1996. The effect of El Niño on U.S. landfalling hurricanes, *Bull. Amer. Meteor. Soc.*, Vol. 77, pp. 773–774.
- Park, L.E. 2012. Comparing two long-term hurricane frequency and intensity records from San Salvador Island, Bahamas. *J. Coast. Res.*, Vol. 28, Issue 4, pp. 891-902. West Palm Beach (Florida), ISSN 0749-0208.
- Paxton, C. (unpublished). Interview with Charlie Paxton. National Weather Service.
- Pielke, R.A., Jr., and Landsea, C.N. 1999. La Niña, El Niño, and Atlantic hurricane damages in the United States, *Bull. Amer. Meteor. Soc.*, Vol. 80, pp. 2027–2033.
- Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk, R.C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffman, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., and van der Plicht, J. 2013. IntCal13 and Marine13 radiocarbon age calibration curves, 0–50,000 years cal BP., *Radiocarbon*, Vol. 55, No. 4, pp. 1869–1887.
- Richey, J.N., Poore, R.Z., Flower, B.P., and T.M. Quinn. 2007. 1400 yr multiproxy record of climate variability from the northern Gulf of Mexico, *Geology*, Vol. 35, pp. 423–426.
- Rosenberg, G., Moretzsohn, F., and García, E.F. 2009. Gastropoda (Mollusca) of the Gulf of Mexico, in: Felder, D.L. and Camp, D.K. (Eds.), *Gulf of Mexico—Origins, Waters, and Biota*. Texas A&M Press, College Station, Texas.
- Saunders, M.A. and Harris, R.A. 1997. Statistical evidence links exceptional 1995 Atlantic hurricane season to record sea warming, *Geophys. Res. Lett.*, Vol. 24, pp. 1255-1258.
- Saunders, M.A. and Lea, A.S. 2008. Large contribution of sea surface warming to recent increase in Atlantic hurricane activity, *Nature*, Vol. 451, pp. 557-460.
- Schwartz, R.K. 1975. Nature and genesis of some storm washover deposits. *CERP Tech*, Memo No. 61, pp. 69.

638

639 Scott, D.B., Collins, E.S., Gayes, P.T., and Wright, E. 2003. Records of prehistoric hurricanes
640 on the South Carolina coast based on micropaleontological and sedimentological
641 evidence, with comparison to other Atlantic Coast records. *GSA Bulletin*, Vol. 115, pp.
642 1027–1039.

643

644 Savarese, M., Loh, A.N., and Trefry, J.H. 2004. Environmental and hydrologic history of
645 Estero Bay: implications for watershed management and restoration, *South Florida*
646 *Water Management District*, Technical Report, pp. 76.

647

648 Smith, S.R., Brolley, J., O'Brien, J.J., and Tartaglione, C.A. 2007. ENSO's impact on
649 regional U.S. hurricane activity, *J. Clim.*, Vol. 20, pp. 1404-1414.

650

651 Stapor, F.W., Jr, Mathews, T.D., and Lindfors-Kearns, F.E. 1991. Barrier-island progradation
652 and Holocene sea-level history in southwest Florida, *J. Coast. Res.*, Vol. 7, No. 3, pp.
653 815–838.

654

655 Stockdon, H.F., Doran, K.J., Thompson, D.M., Sopkin, K.L., Plant, N.G., and Sallenger, A.H.
656 2012. National assessment of hurricane-induced coastal erosion hazards: Gulf of
657 Mexico, U.S. Geological Survey Open-File Report 2012-1084, pp. 51.

658

659 Tartaglione, C.A., Smith, R.S., and O'Brien, J.J. 2003. ENSO impact on hurricane landfall
660 probabilities for the Caribbean, *J. Clim.*, Vol. 26, pp. 2925-2931.

661

662 Van Hengstum, P.J., Donnelly, J.P., Toomey, M.R., Albury, N.A., Lane, P., and Kakuk, B.
663 2014. Heightened hurricane activity on the Little Bahama Bank from 1350 to 1650
664 AD, *Cont. Shelf Res.*, Vol. 86, pp. 103-115.

665 Vaught, K.C. 1989. A classification of the living Mollusca. *American Malacologists*,
666 Melbourne, FL (USA). Vol. XII, pp. 195.

667

668 Webster, P.J., Holland, G.J., Curry, J.A., and Chang, H.R. 2005. Changes in Tropical Cyclone
669 Number, Duration, and Intensity in a Warming Environment, *Science*, Vol. 309, pp.
670 1844–1846.

671

672 Wohlpert, S.L., Savarese, M., and Surge, D. 2007. The development of estuarine systems in
673 southwest Florida: A perspective from the late Holocene history of oyster reef
674 development, *Geol. Soc. Am., Abst. with Programs*, Vol. 39, No. 6, pp. 182.

675

676 Woodruff, J. D., Donnelly, J.P., Mohrig, D., and Geyer, W.R. 2008. Reconstructing relative
677 flooding intensities responsible for hurricane induced deposits from Laguna Playa
678 Grande, Vieques, Puerto Rico, *Geol.*, Vol. 36, pp. 391-394.

679

680 Xie, S., Haiming, X., Kessler, W.S., and Nonaka, M. 2005. Air-sea interaction over the
681 eastern Pacific warm pool: Gap winds, thermocline dome, and atmospheric
682 convection, *J. Clim.*, Vol. 18, No. 1, pp. 5-25.

683

684 Yale, K.E., 1997. Regional stratigraphy and geologic history of barrier islands, west central
685 coast of Florida: Master's Thesis, University of South Florida, Tampa, FL.

686

687 Zilkoski, D.B., Richards, J.H., and Young, G.M. 1992. American congress on surveying and
688 mapping, *Surveying and Land Information Systems*, Vol. 52, No. 3, pp.133-149.