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A 4500-YEAR RECORD OF HURRICANE FREQUENCY IN THE GULF OF MEXICO ARCHIVED IN A NORTH FLORIDA SINKHOLE

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1. INTRODUCTION*

Climate determines the attributes of hurricane populations by dictating the range of environmental conditions that control the formation and life histories of tropical cyclones (Gray 1968, Emanuel 1987, Emanuel 1988, Emanuel et al. 2004). As facilitators of significant heat transport within and between the atmosphere and ocean, tropical cyclones are also important, active components of Earth's climate system (Emanuel 2001, Emanuel 2002, Scott and Marotzke 2002, Sriver and Huber 2007, Korty et al. 2008, Hart et al. 2008, Hart 2009, Sriver et al. 2008). The manner in which tropical cyclone activity and climate co-evolve has critical implications for society and is not well understood.

In this study, we present a 4500-year paleorecord of hurricane frequency in the northeastern Gulf of Mexico. The record, developed from the sediments of a coastal sinkhole, spans a period thirty times longer than instrumental observations. The data presented here are the result of a natural experiment conducted with the Earth's climate system over the last five millennia. Located along Apalachee Bay in the Florida Panhandle, this new site is part of a growing network of paleohurricane records that have already revealed significant, centennial to millennial-scale variability in Atlantic, Caribbean, and Gulf Coast hurricane frequency during the last 5000 years (Liu and Fearn 1993, Liu and Fearn 2000, Donnelly et al. 2001a, Donnelly et al. 2001b, Liu and Fearn 2002, Lambert et al. 2003, Donnelly et al. 2004, Donnelly 2005, Donnelly and Woodruff 2007, Scileppi and Donnelly 2007, Lambert et al. 2008, Woodruff et al. 2008a, Woodruff et al. 2008b).

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2. STUDY AREA

Apalachee Bay, situated in the Big Bend region of Florida's Gulf Coast, encompasses 400 km^2 of the coastal shelf submerged to an average depth of 3 meters (USEPA 1999) (Figure 1a,b). This shallow, concave bay is highly susceptible to extreme storm surges generated by hurricanes that frequent the Gulf of Mexico. Storm tide frequency analysis by a joint probability method suggests that the expected 100-yr surge in the Bay is about 4.5 meters above mean sea level (Ho and Tracey 1975). Storm surges in excess of 3 meters have been observed in the area (Ludlum 1963, Case 1986), and inundation modeling indicates that surges exceeding 8 meters, which would penetrate tens of kilometers inland, can occur under plausible storm conditions (Jelesnianski et al. 1992).

The sediment cores used to develop the paleohurricane record were collected from Mullet Pond (29°55.520'N, 84°20.275'W), a nearly circular, 200 m diameter sinkhole located on Bald Point, a peninsula that protrudes into the westernmost portion of Apalachee Bay (Figure 1b,c). The pond is 350 m from Apalachee Bay and is separated from the bay by a 2 – 3 m high beach dune ridge 200 m to the east (Figure 1c). The pond, situated at the southernmost extent of a salt marsh, had a maximum water depth of 2.3 m and an average surface salinity of 10 psu when cores were collected in January 2008. The local mean tidal range along the open coast at Bald Point is about 0.70 m (NOAA 2009a), and a tidal creek to the north intermittently connects Mullet Pond to the bay.

3. METHODS

3.1 Field work

Four sediment cores were collected along a transect, with two long (~ 6 m) cores (hereafter MLT1 and MLT2) retrieved from the deep, central portion of the pond and two short (~ 2 m) cores collected nearer to the pond's eastern shore (Figure 1c). All four cores

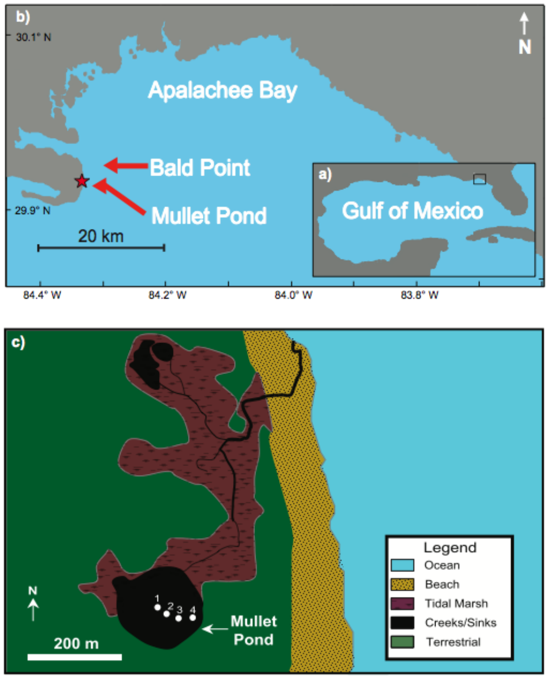

Figure 1 – Panel (a) shows the Gulf of Mexico with the location of Apalachee Bay indicated by the black rectangle. Panel (b) is a regional map of Apalachee Bay showing the Bald Point peninsula just north of 29.9º N and 84.4º W, and the location of Mullet Pond is indicated by the red star. Panel (c) is a local site map showing that Mullet Pond is situated approximately 350 m to the west of the Bay at the southernmost extent of a salt marsh. Numbered core locations are shown as white circles. Mullet Pond is connected to the Bay by the tidal creek to the north but is otherwise separated from the ocean by a 2 – 3 m beach dune ridge 200 m to the east.

were used to identify the spatial extent of the major sedimentary units in the pond; however, laboratory analyses focused on the two longest cores retrieved from the deepest, central portion of the pond, as these would likely provide the longest and highest resolution records. MLT1 and MLT2 were taken in water depths of 2.3 and 2.2 m, respectively, and a handheld GPS unit pinpointed the location of each core.

3.2 Age control

To develop age models for the cores, plant and wood fragments were collected, cleaned, dried and sent to the National Ocean Sciences AMS facility at Woods Hole Oceanographic Institution to be radiocarbon dated. Calendar ages were calculated from ^{14}C ages and associated analytical errors using the IntCal09 calibration curves in the Calib6 program (Reimer et al. 2009). A more detailed, modern age model was needed to date and attribute recent deposits in Mullet Pond to historic hurricanes that impacted the area. The modern age model was constructed through ^{210}Pb dating (Koide et al. 1973, Robbins and Edgington 1975, Faure 1986) and by identifying the sedimentary horizons of the initial rise and subsequent peak in ^{137}Cs activity associated with the advent of (~1954 A.D.) and moratorium on (~1963 A.D.) atmospheric nuclear weapons testing, respectively (Pennington et al. 1973).

3.3 Sedimentary analysis

The sediment cores were sampled at 1-cm intervals, and samples were dried at 105°C for 24 hours and then combusted at 550°C for 2 hours. Before and after each process, samples were weighed to determine the relative contributions of water, organics and inorganics to the mass of the sediment (Dean 1974). The remaining inorganic ash was sieved and the sand size particles (> 63 µm) were retained, dried and weighed to determine the percent coarse by dry bulk weight in each sample.

To understand the evolution of the local environment, foraminifera were censused at approximately 1 m intervals. Standard methods for foraminiferal sample preparation and analysis were employed (Scott and Medioli 1980, de Rijk 1995, de Rijk and Troelstra 1997, Scott et al. 2001, Horton and Edwards 2006). Microfossil assemblages were also analyzed near a few prominent coarse fraction layers in MLT1 and MLT2 to determine if these deposits had a marine origin.

3.4 Storm detection

The coarse fraction time series was high-pass filtered so that it contained only variability on frequencies greater than 30^{-1} yrs^{-1}. This filtering isolated the short-lived deposition events associated with storms from the background composition variations driven by environmental changes occurring on longer timescales. The historic, post-1851 A.D. portion of the record was used to calibrate the storm record by relating recent coarse fraction anomalies to the storm surge events that likely produced them. Due to a lack of a local instrumental surge record, it was first necessary to determine which historic hurricanes most likely produced significant coastal flooding at the site.

The Sea, Lake and Overland Surges from Hurricanes (SLOSH) model was used to identify which historic hurricanes produced the largest storm surges near Mullet Pond. The Atlantic Best-Track Dataset provided storm positions and maximum wind speed estimates at 6-hour intervals going back to 1851 A.D. (Jarvinen et al. 1984, Landsea et al. 2004, Landsea et al. 2008, NOAA 2010b). Rather than maximum wind speed, SLOSH uses the barometric pressure difference between the storm center and the ambient environment (ΔP) as the intensity parameter (Jelesnianski et al. 1992). This quantity was estimated from the Best-Track maximum wind using an empirical wind-pressure parameterization specific to the Gulf of Mexico (Landsea et al. 2004). Similarly, each storm's radius of maximum wind (RMW) was estimated using an empirical expression that relates the climatological RMW of Atlantic hurricanes to storm latitude and ΔP (Vickery et al. 2000).

Bald Point is included in the model domains of three different SLOSH basins: the Apalachicola Basin, the Cedar Key Basin, and the Gulf-Wide Extratropical Basin. Surges were modeled in all three basins for all Best-Track storms having maximum sustained winds of at least 100 knots (SS-Category 3) while within a 500 km radius or 64 knots (SS-Category 1) while within a 200 km radius of Bald Point. The uncertainty in each modeled surge was calculated from the spread among the three basins. For cases where the input parameters are perfectly known, SLOSH is estimated to have a 20 percent analytical error (Jelesnianski et al. 1992), which was also included in the uncertainty estimates for storm surge at Bald Point. The model uses a topographic model derived from National Geodetic Vertical Datum of 1929 (NGVD29), and surges were referenced to this datum.

Once the modern coarse fraction anomalies that corresponded in time to significant historic surges were identified, two calibration strategies using different critical values for storm detection were applied. First, a low threshold (hereafter, LT) that classified most large, modern coarse fraction anomalies as storms was used. Then, a more conservative high threshold (hereafter, HT) was applied to the coarse fraction anomalies. The HT attributed only values equal to or larger than the largest coarse fraction anomaly in the modern record to storm strikes. In this way, two storm event chronologies, one for each detection threshold, were constructed from the coarse fraction anomaly time series.

3.5 Constructing the storm frequency time series

A sliding window was then used to find moving averages of hurricane frequency by dividing the number of storm events within the window by the width of the window (157 years). A 157-yr window was chosen to facilitate comparisons between storm frequency in the instrumental record (1851 – 2007 A.D.) and the paleorecord. A time series of hurricane frequency was produced for both the LT and HT storm chronologies. Owing to the stochastic nature of hurricane landfalls, the number of storms impacting the site would likely vary from one sampled period to the next even if the statistics of Atlantic hurricanes were stationary through time. Thus, some portion of the variability in local storm frequency was due to chance only, while the remainder may have resulted from actual changes in storm climate. To construct confidence intervals for the random portion of the variability, ten thousand 157-year-long artificial bootstrap records were generated. In each bootstrap record, the occurrence of a storm was modeled as a Poisson process with a constant, average storm frequency equal to that of the whole sedimentary record. This method is similar to the one employed in Woodruff et al. (2008a), but the average storm frequency was prescribed by the sediment record itself rather than by an external model. A modeled storm frequency was calculated for each bootstrap sample, and the process was repeated ten thousand times. The 10^{th} and 90^{th} percentiles were then found for each set of modeled storm frequencies. Sets of confidence intervals were found for both the LT and HT records by using their respective average storm frequencies.

4. RESULTS

4.1 Description of Mullet Pond sediments

Visual inspection of the cores together with a CHIRP profile revealed three main sedimentary units in Mullet Pond: basal sand, peat, and an overlying unit of dark, fine-grained sediment (Figure 2a). Loss on ignition and microfossil analysis located the marine transition in the stratigraphy, which divided the fine-grained sediments into a lower fresh lacustrine (pond) unit and an upper brackish lacustrine (pond) unit. Much of the detailed stratigraphy was obscured by gas in the brackish unit; however, a prominent reflector in the upper portion of the sediments could be traced continuously across the basin (Figure 2b). This spatially-uniform reflector corresponded to a sand layer and a peak in inorganic content near 72 cm depth in MLT1 and 64 cm depth in MLT2 (Figure 2b,c). Though MLT2 was slightly longer, MLT1 was extracted closer to the pond's central sediment depot and captured a longer segment of the fine-grained sediments. All of MLT1 and most of MLT2, with total lengths of 601 and 619 cm respectively, were comprised of dark, fine-grained sediment containing abrupt, transient peaks (sub-cm-scale) in sand content (Figure 2c).

4.2 Natural history of Mullet Pond

Based on radiocarbon dating of its sediments, the sinkhole that would eventually become Mullet Pond probably formed when a cavity in the underground limestone collapsed at least 7,000 to 8,000 yrs. B.P. Based on the depth of the overlying sediments in Mullet Pond, the original depression was at least 8 m deep. According to the radiocarbon-based age model, the 0.5 m of freshwater peat between 600 and 550 cm depth in MLT2 was deposited from about 7,000 through 5,800 cal. yrs. B.P. No foramimifera were present in the peat, but a peak in sand and inorganic content at 530 cm depth, dated by the age model to around 5,700 yrs. B.P., was found to contain brackish to shallow marine foraminifera *Ammobaculites dilatus* and *Ammobaculities exiguous*. The presence of these taxa suggested that this earliest coarse fraction layer in Mullet Pond had a marine origin and was likely deposited during a coastal flood. A subsequent increase in baseline sand and inorganic content around the time of this coarse deposit suggested that the site was intercepted by a rising water table and transitioned into a freshwater pond. Ephemeral peaks in coarse and inorganic fraction often accompanied by marine-indicative foraminifera (*Ammobaculites dilates*, *Ammobaculities exiguous* and *Tiphotrocha comprimata*) were frequently deposited after the site became a freshwater pond.

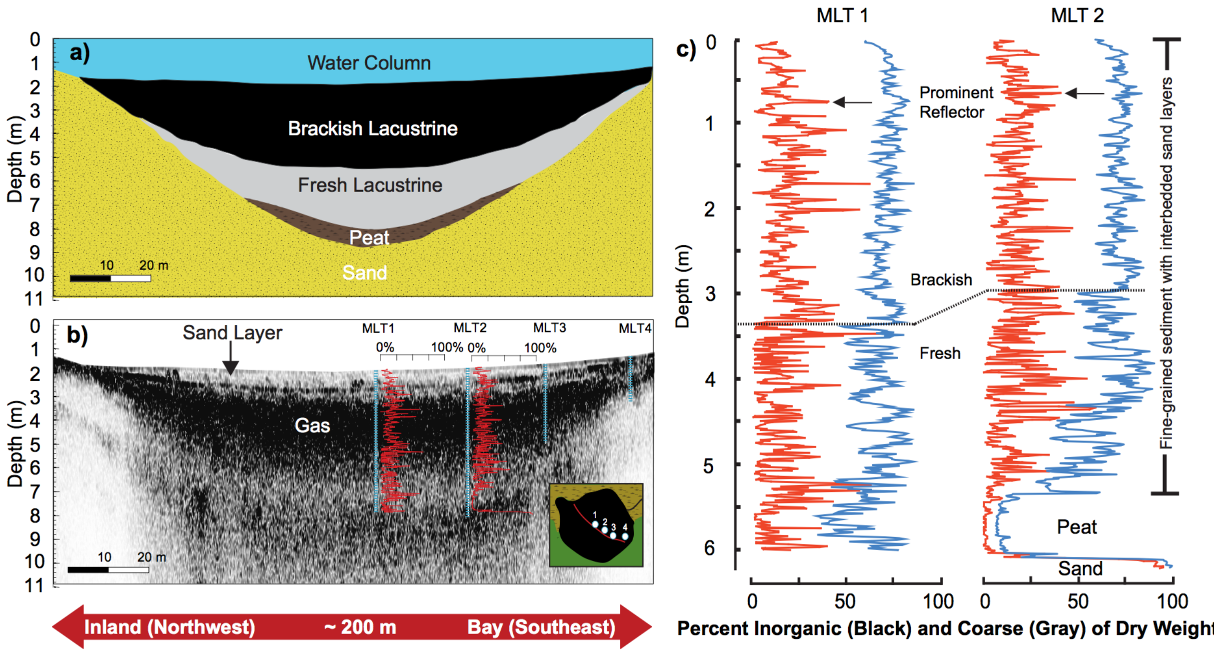

Figure 2 – Panel (a) is a cross-sectional drawing of the major stratigraphic units of the sediments in Mullet Pond: basal sand overlain by peat, then fresh mud, followed by brackish mud. Panel (b) is a CHIRP (sonar) profile of the sediments taken from the northwest (left) to the southeast (right) and approximately transecting all four coring locations. The inset in the lower right corner of panel (b) is a planar map of Mullet Pond showing the coring locations and the path of the transect. The dark, laminar reflector that stretches continuously across the basin near the sediment surface corresponds to a sand layer and a peak in inorganic content near 72 cm depth in MLT1 and 64 cm depth in MLT2. Much of the signal was attenuated by gas in the brackish lacustrine portion of the sediments, and the resulting image of the underlying sediments was obscured. Coring locations are shown as dashed lines, and the coarse fraction by dry weight data for MLT1 and MLT2 are shown to the right of the coring locations. Panel (c) shows both the percent inorganic (blue) and percent coarse (red) content by depth in MLT1 and MLT2 in greater detail. Sand, peat and fine-grained (fresh and brackish) units are denoted. The corresponding depths of the prominent reflector in the CHIRP profile are marked by black arrows in both the MLT1 and MLT2 loss on ignition data.

Rising sea levels (Donnelly and Giosan, 2008) eventually intercepted the pond resulting in a transition to a brackish environment and the development of a salt marsh around the pond perimeter. This transition, dated between 2450 and 2320 yrs. B.P., was indicated by the continuous presence of brackish foraminifera (*Tiphotrocha comprimata, Jadammina macrescens, Ammobaculites sp.,* and *Arenoparella mexicana*) and was accompanied by increases in baseline sand and inorganic content in both MLT1 and MLT2 (Figure 2c).

Given the spatial uniformity of the sedimentary units and deposits in Mullet Pond, MLT1 and MLT2 should both have recorded the same environmental changes and short-lived depositional events through time. However, MLT1 yielded a better-constrained age model, and its higher and remarkably steady sedimentation rate provided the opportunity to develop an event record with uniform, sub-decadal resolution (~ 7 years with 1-cm sampling). For these reasons, further analyses focused on identifying the storm archive contained within the MLT1 record.

4.2 Historic hurricanes and calibration of the paleorecord

SLOSH modeling of the 66 Best Track storms that met the intensity and proximity criteria revealed that fifteen tropical cyclone-induced surges of at least 1 m likely occurred at Bald Point between 1851 and 2007 A.D. A total of eight surges exceeding 2 m, within the provided uncertainty, were modeled in the years 1985, 1966, 1941, 1929, 1926, 1894, 1886 and 1852 (Figure 3c). The largest modeled surge, as much as 5 m, was associated with Hurricane Elena in 1985. The median modeled value of 3.2 m was consistent with observations of an approximately 3 m surge in the area during Hurricane Elena (Case 1986). The modeled 0.8 – 1.6 m surge from Hurricane Eloise in 1975 was also consistent with observations of a small surge in the area (Hebert 1976). The most recent significant surge, caused by Hurricane Dennis in 2005, was modeled to be between 0.9 and 1.6 meters. However, the model underestimated the actual storm tide from Hurricane

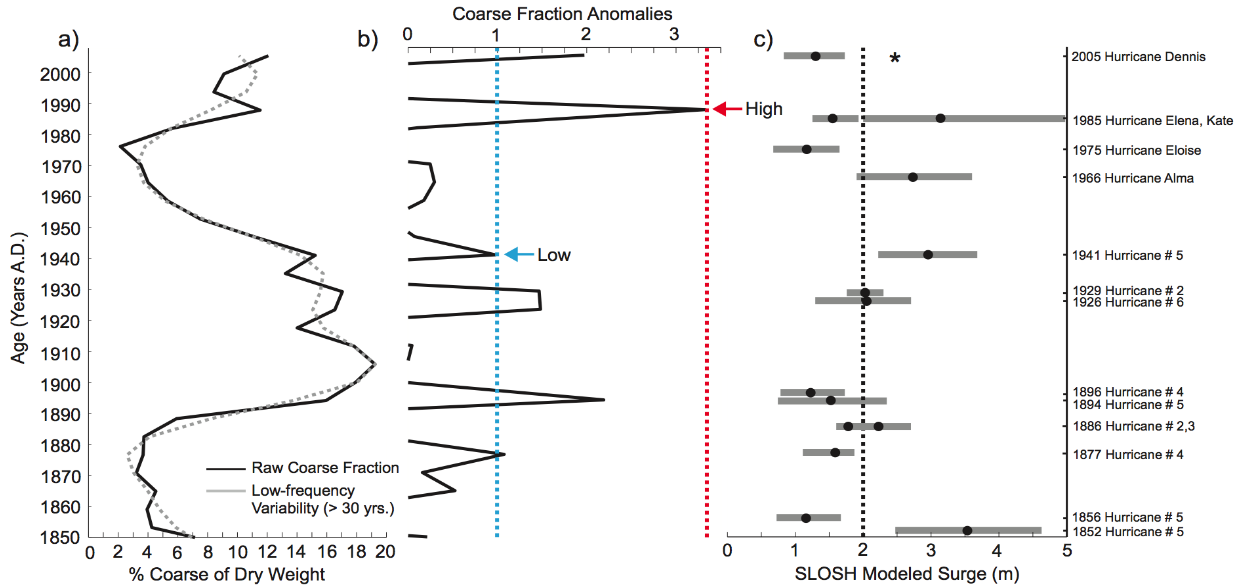

Figure 3 – Panel (a) shows the raw percent coarse data (black) for the uppermost (modern) sediments of MLT1 along with the superimposed low-frequency background (dashed gray curve) produced by applying a low-pass filter to the raw data that removes variability on timescales shorter than 30 years. Panel (b) shows the positive coarse fraction anomalies that result from the subtraction of the low-frequency background from the raw data. These coarse fraction anomalies represent the high-frequency (< 30 years) variability in the modern coarse fraction time series. The coarse fraction anomalies that form the basis for the low (LT, blue dashed line) and high thresholds (HT, red dashed line) used for storm detection were related to hurricanes in 1941 A.D. (gray arrow) and 1985 A.D. (Elena, 1985) respectively. The magnitude of historic (1851 – 2008 A.D.) storms surges at Mullet Pond, which were estimated using the Best Track dataset and the SLOSH model, are shown in panel (c). The estimated maximum surge heights (in meters above NGVD29) for the fifteen events with modeled surges of at least 1 m are shown (black dots) along with the uncertainty (gray bars) in each surge estimate. The shown uncertainty in the surge estimates resulted from the combination of domain-specific factors and the analytical error of the SLOSH model. The A.D. year of occurrence of each significant (> 1 m) surge is labeled to the far right along with either the name of the storm or its number of occurrence within that year. For example, 1941 A.D. Hurricane # 5 was the fifth North Atlantic storm to achieve tropical storm strength in that year. Multiple significant surges occurred in the years 1886 and 1985 A.D. Hurricane # 3 produced the larger of the two surges in 1886 A.D. and Hurricane Elena produced the larger of the two surges occurring in 1985 A.D. The observed surge from Hurricane Dennis near Bald Point is indicated by the asterisk (Morey et al. 2006). The dotted, black line at 2 m indicates the approximate surge height at which the dune ridge to the east of Mullet Pond would be overtopped.

Dennis, which was observed to be 2 – 3 m in western Apalachee Bay (Morey et al. 2006) (Figure 3c). On the other hand, observations of the surge from Hurricane Alma in 1966 suggest that coastal flooding of up to 3 meters did occur as the model indicates but was confined to the east and south of Apalachee Bay (Sugg 1967). Thus, the modeled surge of 1.9 – 3.5 m at Bald Point during Hurricane Alma was likely an overestimate. Reasons for the underperformance of the model in these cases will be discussed later. Surges during earlier storms are even less constrained by observations, so we relied on the SLOSH results to identify which of these historic events likely flooded Mullet Pond.

The largest modern coarse fraction anomalies tended to coincide with significant modeled surges (Figure 3b,c). Five of the six largest coarse fraction anomalies dated to surge events that were modeled or otherwise known to exceed 2 m, within the provided uncertainty. The smallest of these coarse fraction anomalies is likely associated with the 1941 A.D. Hurricane, and this value (~ 1) was selected as the low threshold (LT) for storm detection. All coarse fraction anomalies above the LT in the modern record were coincident with modeled surges caused by historic hurricanes impacting the area. When applied to the older portions of the record, the LT attributed all values meeting or exceeding the 1941 A.D. coarse fraction anomaly to paleohurricane events. However, not every modern surge-producing event was present in the modern sedimentary record, so the paleohurricane record likely also only documented a fraction of all storms impacting the site. The coarse fraction anomaly associated with Hurricane Elena in 1985 (~ 3.3) was selected as the more conservative high threshold (HT) for storm detection. The HT would qualify only the largest, modern coarse fraction anomaly, and coincidentally the largest modeled surge, as a significant event. Obviously this less sensitive detection method resulted in a greater underestimation of event occurrence; however, using the HT provided a higher degree of certainty that values exceeding the threshold correspond to significant coastal floods in the past and served as a sensitivity analysis of the result to the threshold value used.

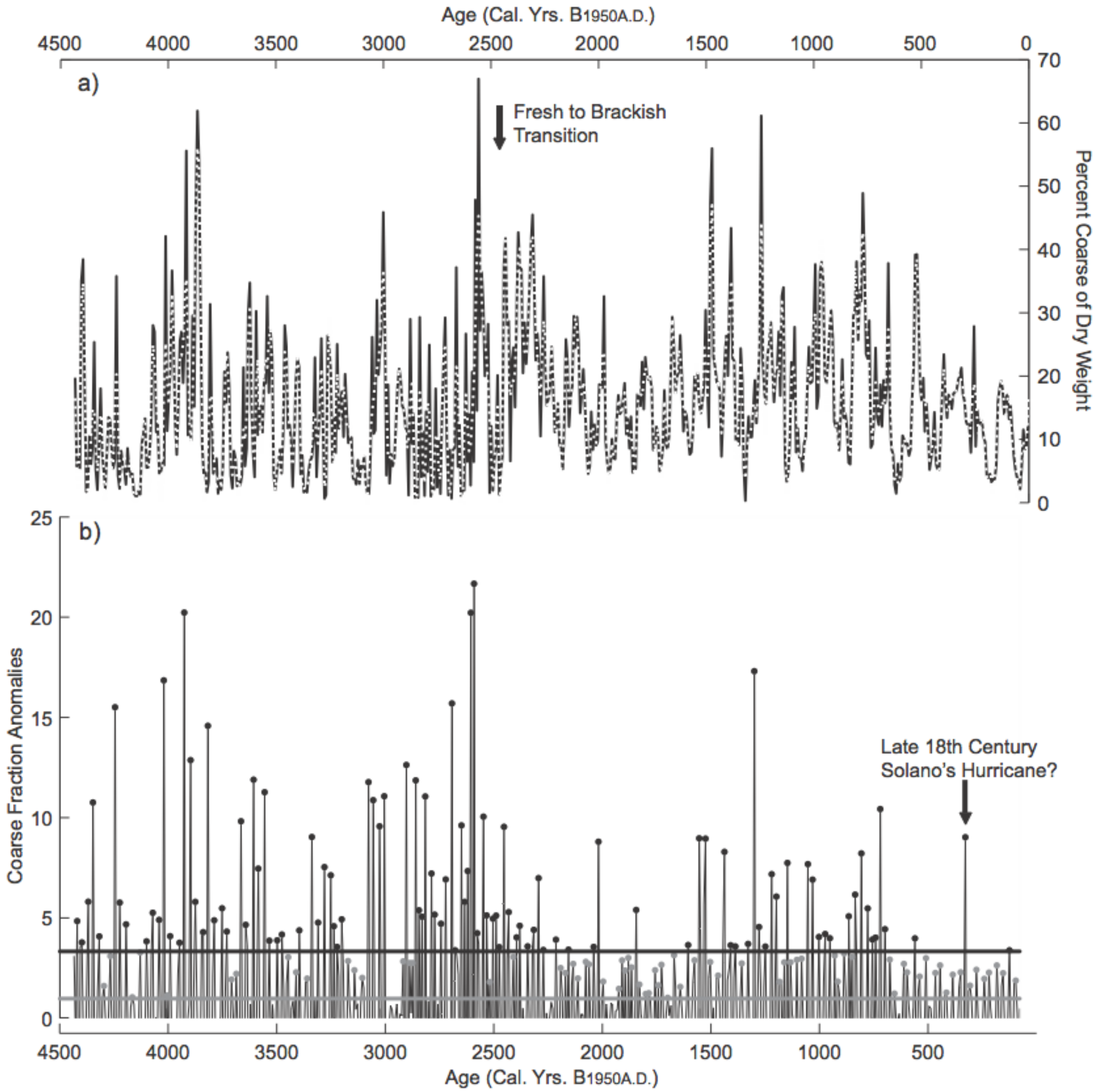

Figure 4 – Panel (a) shows the raw coarse fraction time series from MLT1 (solid black) with the dotted portion outlining the low-frequency, (> 30 year) background variability of the time series. The approximate location of the fresh to brackish transition, as suggested by a shift in the coarse fraction, inorganic content and microfossil assemblages, is indicated by a black arrow. Panel (b) displays the corresponding coarse fraction anomalies, which represent the high-frequency (< 30 year) variability of the raw time series. 177 anomaly values (gray circles) exceeded the low threshold (LT, gray line) and 107 anomaly values (black circles) exceeded the high threshold (HT, black line). A large coarse fraction anomaly (black arrow) dated to the late 18th Century is possibly related to Solano's Hurricane of 1780 A.D.

4.3 Event frequency in the modern and paleorecord

Since 4500 cal. yrs. B.P., 177 events exceeded the LT and 107 events exceeded the HT in MLT1 (Figure 4b). The resulting average event frequencies were 3.9 events/century and 2.4 events/century for the LT and HT cases respectively. The corresponding event frequencies in the post-1851 A.D. portion of the sediment record were 3.8 events/century when the LT was applied and 0.6 events/century when the HT was applied. Thus, modern event frequency was similar to the long-term average when events were identified using the LT; however, modern event frequency was four times lower than the long-term average when the HT was used. According to the event frequency time series constructed with the HT, the occurrence of events at Mullet Pond must have been significantly more common during part of the paleorecord than they were in the 19th and 20th centuries.

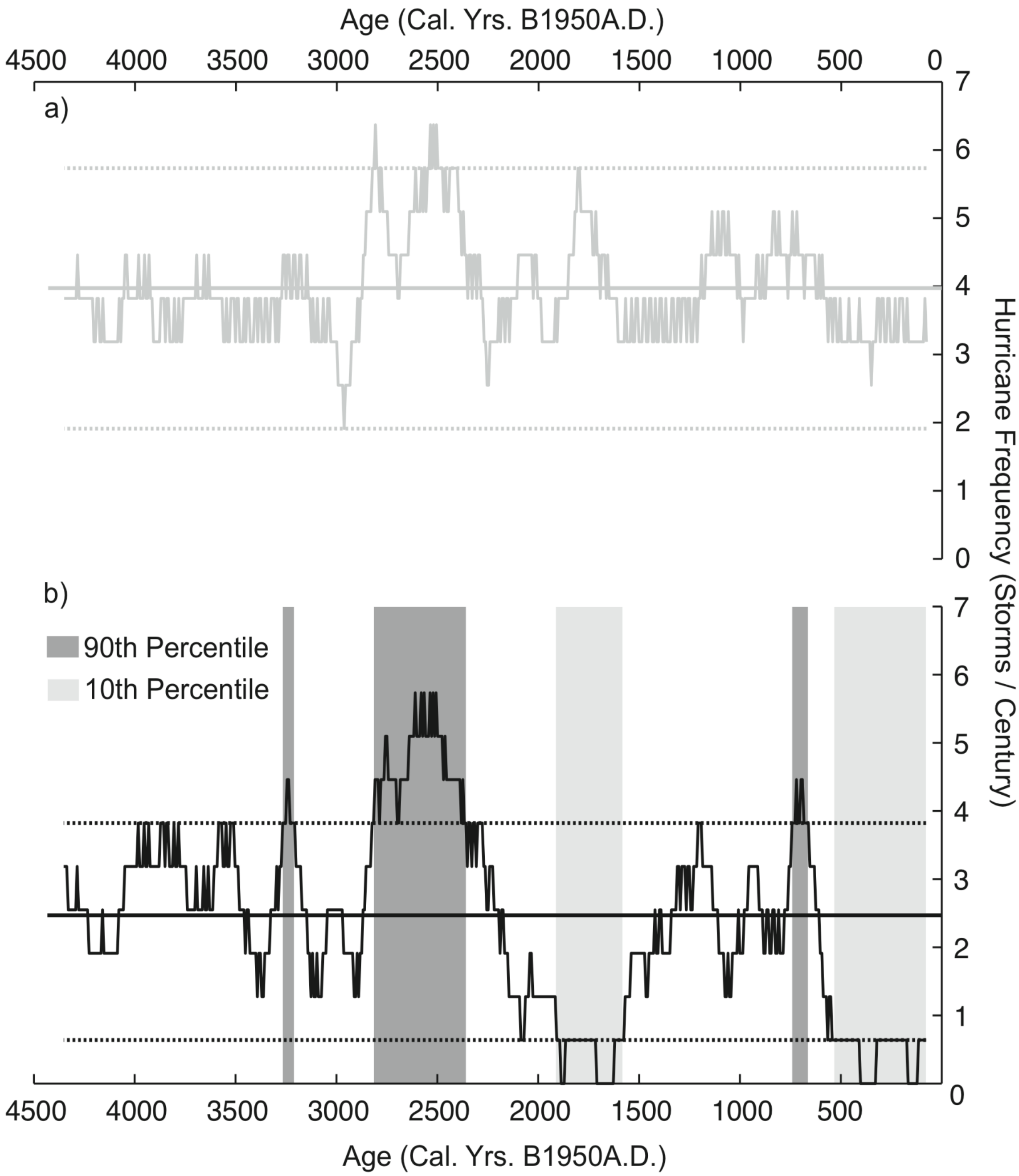

Figure 5 – Panel (a) is the MLT1 time series of hurricane frequency normalized to events per century (gray curve) when all coarse fraction anomalies exceeding the LH were attributed to storms. Due to truncation required by the 157-year sliding window, the time series spans the period from 4294 to 21 cal. yrs. $B_{1950A.D.}$. The solid gray line is the mean storm frequency (~ 4.1 storms per century) over the entire length of the record, while the dashed gray lines represent the 90^{th} (upper line, ~ 5.7 storms per century) and 10^{th} (lower line, ~ 1.9 storms per century) percentiles of storm frequency based on ten thousand 157-year-long bootstrap records. In the bootstrap records, storm occurrence was modeled as a Poisson process with an average frequency equal to that of the mean storm frequency for the entire sediment record (again, ~ 4.1 storms per century). Panel (b) is the same analysis, but only coarse fraction anomalies exceeding the HT were attributed to storms. In this case, the record mean storm frequency over the entire 4450-year period (solid black line) was approximately 2.5 storms per century. The dashed black lines represent the 90^{th} (upper line, ~ 3.8 storms per century) and 10^{th} (lower line, ~ 0.6 storms per century) percentiles based on the bootstrap method. Darker gray shaded portions of panel (b) highlight periods with storm frequency that exceeded the 90^{th} percentile of what would be expected by chance. The lighter gray periods were less active times in the record when storm frequency was in the bottom 10^{th} percentile of what would be expected by chance.

The LT-based time series showed relatively little variability with event frequency only briefly exceeding the 90th percentile of the bootstrap records (5.7 events/century) around 2600 and 2800 cal. yrs. B.P. (Figure 5a). Of the ten thousand 157-year-long bootstrap records modeled with the record mean HT frequency of 2.4 events/century, only the most active 10 percent had more than 3.8 events/century and the least active 10 percent had fewer than 0.6 events/century (Figure 5b). Three periods in the HT-based time series exhibited event frequencies above the 90th percentile of the bootstrap records: a 50 – 100-year period around 3300 cal. yrs. B.P. with about 4.5 events/century, 2800 to 2400 cal. yrs. B.P. with a peak of 5.5 events/century near 2500 cal. yrs. B.P., and an ~ 100-year period with about 4.5 events/century around 700 cal. yrs. B.P. Two periods in the record had event frequencies in the bottom 10th percentile of the bootstrap records. These periods, each averaging fewer than one event every 200 years, occurred between 1800 and 1600 cal. yrs. B.P. and 500 cal. yrs. B.P. through present (Figure 5b). Even if large coarse fraction anomalies resulted from hurricane-induced surges, factors other than tropical cyclone activity, which include sea level and coastal morphology changes, may have influenced flooding frequency through time. However, we will argue later that this record primarily documents variability in storm climate over the last 4500 years.

5. DISCUSSION AND CONCLUSIONS

5.1 Coarse fraction anomalies as hurricane deposits

The mostly fine-grained sediments of Mullet Pond were shown to contain abrupt peaks (< 1-cm thick) in sand content that represent sedimentation occurring on timescales no longer than the sampling resolution of ~ 7 yrs. Transient increases in the abundance of larger (> 63 um) particles in the pond sediments could be caused by short-lived transitions to a higher-energy environment, which would occur during flooding events. The sandy soils of the area provide a well-drained landscape, so terrestrial runoff from freshwater flooding is an unlikely explanation for the deposits (Puri and Vernon 1964). Moreover, some of the coarse deposits examined were found to contain marine forams, some of which live only in offshore environments. The presence of offshore taxa suggests that the coarse sediment was likely transported by very dynamic coastal flooding. Given the relative seismic stability of the region, tsunamis in the Gulf of Mexico seem to be an unlikely cause of the coastal floods. Storm-induced coastal flooding remains as the most likely mechanism for the production of the thin, coarse-grained deposits in Mullet Pond. The CHIRP profile of Mullet Pond (Figure 2b), though mostly obscured by gas, suggested that the upper sediment stratigraphy is spatially uniform across the basin. Horizontal continuity of the coarse deposits would indicate they originated when sand suspended by surge and wave action was advected over the dune ridge or through the marsh and then subsequently settled out after the flooding had subsided. While coastal flooding can occur during non-tropical storms, every significant coarse fraction anomaly in the modern portion of MLT1 was contemporaneous with a historic tropical cyclone either documented or deemed capable via modeling of generating coastal flooding at the site. We conclude that coarse fraction anomalies in the MLT1 record provide a reasonable proxy for local tropical cyclone-induced storm surges.

5.2 Surges and sedimentary signatures of historic hurricanes

The magnitude of a hurricane's local storm surge is likely the best measure of whether or not a storm has inundated Mullet Pond and produced a storm deposit. However, no instrumental storm tide observations exist for the site, and storm surge modeling can be highly uncertain. To ensure that the modeled surges reflect some of these uncertainties, the flooding from the Best Track storms affecting the area were modeled using three different grid domains, each with its own set of advantages and limitations. The Apalachicola (APC) basin provides the highest model resolution at Bald Point but neglects the effects of remotely-produced, coastally-trapped Kelvin waves, which are sometimes generated beyond the model domain and can travel into the area of interest. Such waves can contribute significantly to the overall surge along this coastline. Hurricane Dennis in 2005 generated a coastally-trapped wave, and the operational use of the spatially-limited APC basin to forecast the anticipated surge led to a dramatic under-prediction of the coastal flooding in Apalachee Bay (Morey et al. 2006). The Cedar Key (CDR) basin includes more of the coastal shelf and, thus, can better simulate trapped coastal waves when they occur; however, this basin has lower spatial resolution at Bald Point. The Gulf-Wide (EGLL) basin includes the whole central and northern Gulf of Mexico and does the best job of simulating trapped waves, but this basin also has the coarsest resolution and does not permit surges to penetrate inland.

Even though all three domains were employed, the reported storm tides for a few historic events fell outside the range of their modeled storm surges. These discrepancies likely arose from uncertainties in the SLOSH model input. Simplifying assumptions including the use of parameterizations for the RMW, wind field, and wind-pressure relationships as well as the omission of astronomical tides, wind waves, and wave setup may account for some of the differences between the modeled surges and observed storm tides. Errors in the Best Track storm intensity or position data would also add uncertainty particularly in the earlier years of the dataset. However, the intent was not to precisely hindcast historical storm tides, but rather to sieve through the hundreds of Gulf storms in the Best-Track data for the few historic storms likely represented in the sediment record.

Nearly every significant coarse fraction anomaly coincided with a significant (at least 2 meters), historic surge; however, not every historic hurricane with a modeled surge exceeding 2 meters was detected in the recent sediment record. As previously discussed, the actual storm tides may have been smaller than the modeled surges in some cases. Moreover, the age model for the last half of the 19th Century was based on an interpolation between the upper ^{137}Cs and ^{210}Pb constraints and a radiocarbon date at 80 cm (~ 545 cal. yrs. B.P.). The more tenuous 19th Century age control may have prevented the proper attribution of significant coarse fraction anomalies to large, modeled surge events such as the one associated with the 1852 A.D. Hurricane (Figure 3b,c). While the sediment record may not document every hurricane that affected the area since 1851 A.D., the correspondence of the largest, recent coarse fraction anomalies with the most significant documented hurricane events in the area is encouraging.

The largest coarse fraction anomaly in the last 500 years was dated to the late 18th Century (Figure 4b). In an independent, tree-ring based paleohurricane record from southern Georgia, hurricane rainfall events over a 220-year period have been identified by the unique oxygen isotope anomalies they leave in tree cellulose (Miller et al. 2006). The investigators were able to detect the passage of historic storms as far away as 400 km from the site, and Bald Point is only 150 km to the southwest. A lone, large isotopic anomaly in the late 18th century was absolutely dated by ring counting to 1780 A.D.—the deadliest documented Atlantic hurricane season with at least 24,000 fatalities in the U.S. and Caribbean. Solano's Hurricane, one of three "Great" hurricanes that year, was named after a Spanish admiral whose mission to seize the Florida Panhandle from the British was thwarted when the storm scattered his fleet and killed half of his 4,000 men (Emanuel 2005a). After causing many deaths at sea, the storm made landfall west of Apalachee Bay and then likely tracked near the tree-ring record site (Ludlum 1963). The coarse layer in Mullet Pond roughly dates to the time of Solano's Hurricane, and indicates that this storm may have remained strong enough at landfall to generate a large surge in Apalachee Bay.

While the largest events were represented in the record, some smaller events likely went undetected resulting in an underestimate of the number of storms impacting the site through time. While 66 historic storms met the intensity and proximity criteria for SLOSH modeling and 15 of these were modeled to have surges of at least 1 m at the site, only six modern storm deposits were detected in the MLT1 record. This translates into a detection rate of approximately 9 percent of all modeled storms and 40 percent of storms with 1+ m of modeled surge at the site, respectively. Undercounting may also have occurred as a result of limited sampling resolution. For example, the hurricanes of 1894 and 1896 A.D. occurred in such quick succession that they could not be distinguished as two events given the approximately 7-year resolution of the sediment record (Figure 3b,c). Multiple storms occurred in the years 1985 and 1886 A.D., and these storms would also be lumped together as single events. Undercounting of paleohurricanes likely occurred throughout the record, and more storms were probably missed during periods of greater storm frequency (Woodruff et al. 2008a). Therefore the actual amplitude of the storm frequency variations through time was likely larger than what was calculated from the MLT1 record (Figure 5). This quantitative limitation qualitatively reinforces the result that the frequency of hurricanes in the northeastern Gulf of Mexico has varied significantly over the last 4500 years.

5.3 Site sensitivity to storm surge through time

Much of the criticism against using the historic Atlantic hurricane record to detect secular trends concerns the improvement of storm detection and observation through time (Landsea 2007, Chen et al. 2009). A similar criticism could be leveled against the paleohurricane record contained in Mullet Pond, which should have experienced increasing susceptibility to storm surges as sea level rose and, therefore, should have become a more complete record of storm activity toward present. Debate exists over the evolution of sea level in the Gulf of Mexico during the Holocene. Some investigators have proposed that Gulf sea level has increased in a generally smooth and continuous fashion (Otvos 2001, Törnqvist et al. 2004, Wright et al. 2005, Donnelly and Giosan 2008, Milliken et al. 2008, Simms et al. 2009), while more complex sea level curves for the region have also been suggested (Stapor et al. 1991, Tanner 1992, Morton et al. 2000). Dating of relic beach ridges along the northern Gulf of Mexico has been offered as evidence for periods of higher than modern sea level (~ +2m) during the mid-Holocene (Morton et al. 2000, Blum et al. 2003). However, if sea level had been significantly higher than modern at any time in the last 7,000 years, then a nearshore or open marine sequence should be evident from the lithology and microfossil profile of MLT2, which spans the last 8000 years. No such evidence for a significant Holocene sea-level highstand exists in the MLT2 chronology. The combined effects of sea-level rise and shoreline retreat should have colluded to increase the frequency of hurricane inundations through time. However, the record does not provide evidence for such a trend and possesses variability that cannot be explained by steady sea-level rise. In fact, sea level along the Gulf Coast of Florida has been placed at 1.2 to 1.5 m below modern levels around 2500 yrs. B.P. (Wright et al. 2005), when storm frequency peaked in the Mullet Pond record. With the 100-yr. coastal flood level purported to be 4.5 m (Ho and Tracey 1975), the surge potential in Apalachee Bay is much larger than the proposed sea level rise that occurred during the period spanned by the MLT1 record. For these reasons, we deduce that the changes in storm frequency suggested by the MLT1 record primarily reflect variability in storm climate rather than changes in site sensitivity.

5.4 Local and large-scale storm climate: comparisons with other paleohurricane records

Given the stochastic nature of hurricane landfalls, changes in the frequency of storms at one particular site may not necessarily reflect larger-scale changes in storm frequency. The discrepancy between site-specific and basin-wide activity may be largest when short time periods are considered. For this reason, any very recent trend in Atlantic-wide hurricane frequency caused by anthropogenic climate change would be nearly impossible to detect in a single sedimentary record. When longer time periods are considered, changes in local hurricane frequency are more likely to reflect larger-scale changes in storm climate. Other sediment-based paleohurricane records from the Caribbean, Northeastern U.S. and the northern Gulf of Mexico have documented significant centennial to millennial-scale variability in hurricane frequency similar to that present in the Mullet Pond reconstruction, though the timing and extent of the variability differs among the records (Liu and Fearn 1993, Liu and Fearn 2000, Scileppi and Donnelly 2007, Donnelly and Woodruff 2007).

Liu and Fearn (1993, 2000) identified low-frequency variability in the number of visible sand layers deposited by hurricanes impacting Western Lake, Florida. They suggested that long-term shifts in atmospheric circulation directed the majority of hurricanes toward either the Gulf or U.S. East Coast resulting in alternating hyperactive (from 3400 to 1000 cal. yrs. B.P.) and quiescent storm phases (between 5000 to 3400 cal. yrs. B.P. and after 1000 cal. yrs. B.P.) in the Gulf of Mexico. This Bermuda High Hypothesis has found support from studies of the instrumental record that have identified high-frequency variability in the dominant tracks of modern Atlantic hurricanes (Elsner et al. 2000, Elsner 2003, Holland 2007, Kossin and Camargo, 2009). However, a paleohurricane record based on salt marsh cores from Alder Island, NY exhibited a period and phase of variability similar to that of the Gulf Coast record (Scileppi and Donnelly 2007). Hurricane inundation layers were most abundant in the marsh between 3200 and 700 cal. yrs. B.P. but were rare between 700 and 300 cal. yrs. B.P. Another record documenting intense hurricane strikes in the Caribbean indicated a similar pattern of activity over the last 5000 years in Vieques, Puerto Rico (Donnelly and Woodruff 2007). The stormiest intervals at Vieques were from 5500 to 3700 cal. yrs. B.P., 2500 to 1000 cal. yrs. B.P. and after 250 cal. yrs. B.P., while the calmest periods occurred 3700 to 2500 cal. yrs. B.P. and 1000 to 500 cal. yrs. B.P. The authors argued that the local frequency of storms at Vieques was influenced by the low-frequency behaviors of the ENSO and the West African Monsoon—a hypothesis inspired by the instrumental record (Goldenberg and Shapiro 1996) and supported by paleorecords of these phenomena (Moy et al. 2002, Nguetsop et al. 2004). In contrast to storm track-driven changes, this variability could drive large-scale, basin-wide variations in storm frequency and possibly intensity. Another recently developed paleohurricane record based on marsh sediments from Mattapoisett, Massachusetts contained evidence for significant, long-term variability in the number of hurricane strikes in New England as well (Boldt et al., In Press). The Mullet Pond reconstruction shares many similar features with a 1500-year reconstruction of basin-wide landfalling Atlantic hurricanes, which was based on a compilation of several paleohurricane records including those already discussed (Mann et al. 2009) (Figure 6a,b).

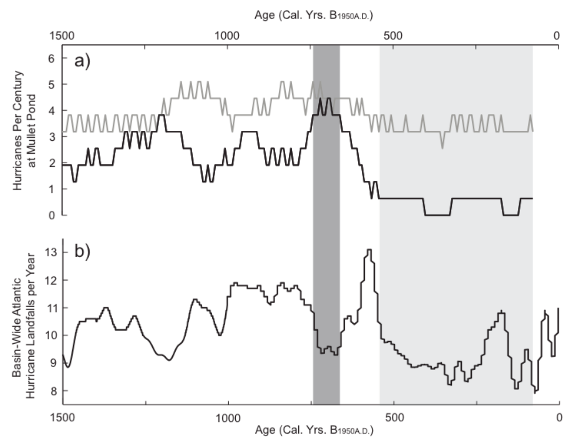

Figure 6 – Panel (a) is the time series of hurricane frequency at Mullet Pond from 1500 to 21 cal. yrs. $B_{1950A.D.}$. The gray curve is the LT time series and the black curve is the HT time series. The darker gray shaded portion highlights a period with storm frequency that exceeded the 90th percentile of what would be expected by chance. The period shaded in light gray saw fewer hurricanes with storm frequency in the bottom 10th percentile of what would be expected by chance. Panel (b) is a reconstruction of annual basin-wide Atlantic hurricane landfalls based on a composite of various paleohurricane reconstructions from the Caribbean, U.S. East Coast and the northern Gulf of Mexico for the period 1450 – 100 yrs. $B_{1950A.D.}$ (Mann et al. 2009).

Both the paleorecord compilation and the Mullet Pond record show increasing storm frequency between 1500 and 1000 cal. yrs. B.P. and a prolonged decline in hurricane landfalls beginning after 600 cal. yrs. B.P. The spike in hurricane landfalls that occurs just prior to 600 cal. yrs. B.P. in the Mann et al. (2009) reconstruction is present in the Mullet Pond record but was dated approximately 100 years earlier. This discrepancy may be real or, more likely, it is the result of differences between the Mullet Pond age model and the merged age models and associated uncertainties of the other paleohurricane reconstructions.

While the available Atlantic paleohurricane reconstructions share some similar characteristics, significant differences also exist. Many factors contribute to these differences. The local sedimentary expression of a basin-wide change in overall Atlantic hurricane frequency and/or intensity could be quite different depending on a host of site-specific and regional factors. Discrepancies in hurricane reconstructions may reflect differences in local storm frequency and intensity distributions, age models, temporal resolutions of the records, flooding thresholds, local sea-level rise and associated geomorphological changes. Mean storm frequencies over the last 2500 years were 0.32 storms/century at Western Lake, 0.52 storms/century at Alder Island, 0.68 storms/century at Vieques, 1.2 storms/century at Mattapoisett, and between 1.8 and 4 storms/century at Mullet Pond depending on whether the HT or LT time series was considered. This wide range of local landfall rates results both from geographic differences in the number and intensity distribution of hurricanes affecting each region and from the local susceptibility of each site to inundation by storm surge.

The Western Lake, Vieques and Alder Island records were developed from sites that are relatively difficult to inundate; therefore, these records likely documented only the largest hurricane-induced surges (Liu and Fearn 2000, Scileppi and Donnelly 2007, Woodruff et al. 2008a, Woodruff et al. 2008b). As suggested by their much higher paleohurricane frequencies, Mullet Pond and Mattapoisett Marsh are more susceptible to smaller storm surges and can be inundated by a broader range of surge events. Changes in the intensity distribution of hurricanes occurring in concert with changes in storm frequency could cause the frequency of storm deposits in sites with different flooding susceptibilities to diverge. Numerical modeling of late 21st century hurricane climatology has suggested that declines in overall Atlantic hurricane frequency could occur simultaneously with a broadening of the intensity distribution of hurricanes leading to fewer but more intense storms (Emanuel et al. 2008, Gualdi et al. 2008, Knutson et al. 2008, Zhao et al. 2009, Bender et al. 2010). However, recent warming and increased hurricane frequency in the Atlantic has purportedly been accompanied by a disproportionate increase in the occurrence of intense hurricanes (Emanuel 2005b, Webster et al. 2005, Hoyos et al. 2006, Elsner et al. 2008, Jagger and Elsner 2008). When considering the climate system feedbacks likely associated with the atmospheric and upper ocean anomalies caused by tropical cyclones (Hart et al. 2008, Hart 2009), it seems unlikely that significant changes in the frequency of storms would not also change their intensity statistics.

The deposits attributed to Hurricane Elena and Solano's Hurricane, both major events at the site, were very prominent in the record. However, the magnitude of the coarse fraction anomaly associated with a hurricane is not necessarily an indication of storm intensity, nor is it necessarily an indication of storm surge magnitude. Even if coarse fraction anomalies do scale with flooding magnitude, the local storm surge may only weakly correlate with the local intensity of a storm, which itself provides only a minimum estimate of the absolute storm intensity. However, some of the most sand-rich deposits do contain evidence of extremely energetic events. Some coarse deposits sampled for microfossils contained marine taxa common to deeper, offshore environments. These taxa, not typical of a coastal pond or salt marsh, included *Brizalina spathulata, Ammonia beccarii* and radiolarians. One of these deposits dated to around 2150 cal. yrs. B.P., when sea level was about a meter lower than modern (Wright et al. 2005). The presence of these taxa suggests it was produced by a violent event capable of transporting offshore sediment a considerable distance. Understanding the relationship between storm frequency and intensity distribution during the last few thousand years will require a multi-site approach. A suite of records from closely-spaced sites with different flooding thresholds but the same history of storm strikes is needed to quantify the relative contributions of storm frequency and intensity to variability in hurricane activity. More thorough and detailed microfossil analysis, though very time consuming, could also aid in classifying how energetic a flooding event was by identifying the provenance of the marine sediment in the resulting sand deposit.

5.6 Atlantic hurricanes and climate during the last 4500 years

The Mann et al. (2009) reconstruction attributes periods of more frequent hurricane landfalls in the last 1500 years to times of warmer Atlantic SSTs and more La Niña-like conditions. Similarly, hurricane frequency at Mullet Pond nearly mirrors SSTs in the Sargasso Sea (Keigwin 1996), with more hurricane activity during the Medieval Climate Anomaly (~ 1200 to 600 yrs. B.P.) and less hurricane activity during the Little Ice Age (~ 400 – 150 yrs. B.P.) (Figure 8b). However, a 1400-year Mg/Ca SST reconstruction from the Pigmy Basin in the northern Gulf of Mexico (Richey et al. 2007) reveals a somewhat tenuous correspondence between surface temperatures in the Gulf and hurricane frequency at Mullet Pond. A significant drop in Gulf SST (~ 2°C) around 1000 cal. yrs. B.P. was accompanied by a decrease in the frequency of HT storms but an increase in frequency of LT storms (Figure 7a,b). A more significant decrease in hurricane frequency occurred around 600 cal. yrs. B.P. when a decline in *G. sacculifer* abundance (Figure 7c) in the Pigmy Basin suggests reduced advection of Caribbean surface waters into the Gulf of Mexico. This hydrologic shift may indicate a shoaling of the mixed layer caused by reduced incursion of the Loop Current into the eastern Gulf of Mexico (Poore et al. 2004), which would lower the ocean heat content available to tropical cyclones in the Gulf without necessarily lowering the SSTs.

The climatological maximum potential intensity (MPI) of tropical cyclones is greater in the Gulf of Mexico than anywhere else in the Atlantic Basin during hurricane season (Emanuel 1987, 1988); however, few Gulf storms ever reach their MPI. Although SSTs in the Gulf are warm enough (≥ 26 ºC) to support tropical cyclone development in the summer months, the mixed layer of warm surface waters is quite shallow with the 26 ºC isotherm typically only 30 – 40 m below the surface (Chouinard et al. 1997). As storms intensify, they quickly mix up cooler waters from below, and this

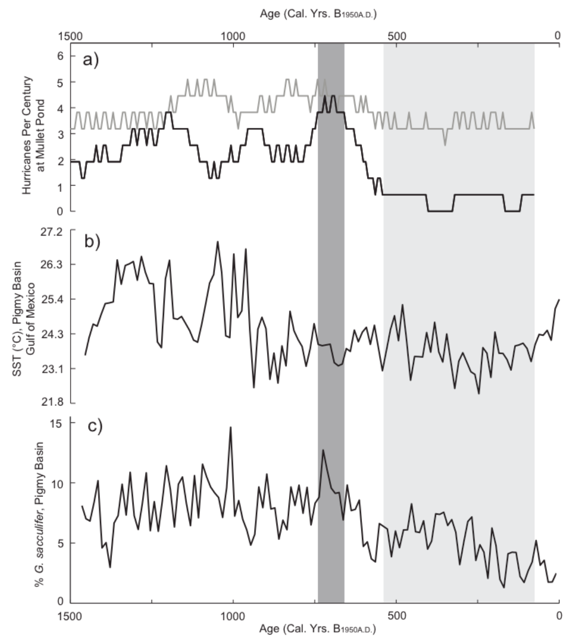

Figure 7 – Panel (a) is the time series of hurricane frequency at Mullet Pond from 1500 to 21 cal. yrs. $B_{1950A.D.}$. The gray curve is the LT time series and the black curve is the HT time series. The darker gray shaded portion highlights a period with storm frequency that exceeded the 90th percentile of what would be expected by chance. The period shaded in light gray saw fewer hurricanes with storm frequency in the bottom 10th percentile of what would be expected by chance. Panel (b) is a foraminiferal Mg/Ca record of annual mean sea-surface temperature in the northern Gulf of Mexico based on an ocean sediment core taken from the Pigmy Basin (27°11.61'N, 91°24.54'W) (Richey et al. 2007). Panel (c) is the time series of *G. sacculifer* abundance in the same core used to develop the SST record shown in panel (b). Greater (lesser) abundance of *G. sacculifer* is indicative of increased (decreased) Caribbean surface water input into the Gulf of Mexico and is interpreted as increased (decreased) Loop Current penetration into the Gulf (Richey et al. 2007).

process limits further storm development (Emanuel et al. 2004). In the Loop Current, however, the 26 ºC isotherm can be as deep as 200 m below the surface providing several times more available energy to developing cyclones and limiting the role of storm-induced upwelling (Goni and Trinanes 2003). While summertime SSTs are nearly homogenous in the Gulf, the spatial distribution of historic Gulf hurricane intensities is not (Cooper 1992). Some of the strongest, historic Gulf hurricanes achieved their exceptional intensities while interacting with the Loop Current or its associated Warm Core Eddies (Shay et al. 2000, Hong et al. 2000). Hurricane Camille, which made landfall along with U.S. Gulf coast in 1969 with winds exceeding 300 km/hr, is thought to have traveled up the axis of the Loop Current (Ly and Kantha 1993, Emanuel 1999, Emanuel et al. 2004). The deep, warm waters of the Loop Current enter the Gulf through the Yucatan Channel and flow northward before making a clockwise loop and exiting the Gulf through the Florida Strait. Reconstructions of Loop Current penetration into the eastern Gulf of Mexico during the Holocene have been found to exhibit significant centennial (200 – 230 yrs.) and millennial-scale (~ 1500 yrs.) variability (Poore et al. 2003). The significant variability in storm frequency detected in the Mullet Pond record may, in part, reflect the behavior of the Loop Current on these timescales. Given the association of the Loop Current with the most extreme historic hurricanes, long-term changes in the extent of the Loop Current in the Gulf could also provide support for and explain previously postulated catastrophic hurricane regimes along the Gulf coast (Liu and Fearn 2000). Loop current variability on these timescales is thought to be related to migrations of the Intertropical Convergence Zone (ITCZ) (Poore et al. 2003), which may also impact Atlantic hurricane activity through other mechanisms. The recent decline of both the Loop Current's influence and storm frequency in the Gulf may have been related to a southward shift in the ITCZ that occurred around 600 cal. yrs. B.P. (Peterson et al. 1991, Haug et al. 2001, Richey et al. 2007).

ENSO variability has been shown to strongly impact Atlantic tropical cyclone activity on the inter-annual timescale. Centennial-to-millennial scale variability in the ENSO was also found to correspond with paleohurricane regimes in the Caribbean (Donnelly and Woodruff 2007), with more frequent El Niño warming events coinciding with periods of fewer intense hurricanes at Vieques. Though the correspondence between the Mullet Pond record and reconstructed El Niño frequency (Moy et al. 2002) is somewhat tenuous, it would appear more storms impact the northern Gulf when warm ENSO events are more frequent (Figure 8a,c). While this finding appears to be in conflict with the Vieques record, it may also suggest that the nature of Pacific SST variability and its effects on Atlantic and Gulf Coast hurricane frequency, intensity, and track may be quite complicated. The intensity distribution of Atlantic hurricanes, for instance, may actually be broadened by El Niño events thereby increasing the likelihood of the most intense storms while lowering the overall frequency of hurricanes (Jagger and Elsner 2006, Jagger and Elsner 2008). Therefore, more frequent El Niño events could either increase or decrease the frequency of inundation depending on the flooding threshold (sensitivity) of the site. This effect may explain some of the differences between the Mullet Pond record and the Western Lake record—two sites separated by less than 200 km but each having very different flooding thresholds. Moreover, different types of ENSO states may affect Atlantic hurricane frequency in spatially non-uniform ways. Eastern Pacific warming (EPW, El Niño) events decrease the frequency of landfalls in both eastern North America and the Caribbean, while eastern Pacific cooling (EPC, La Nina) events tend to increase the likelihood of landfall in these areas. Central pacific warming events, however, may substantially increase the number of Atlantic tropical cyclones impacting North America while diminishing the threat in the Caribbean (Kim et al. 2009). The recently

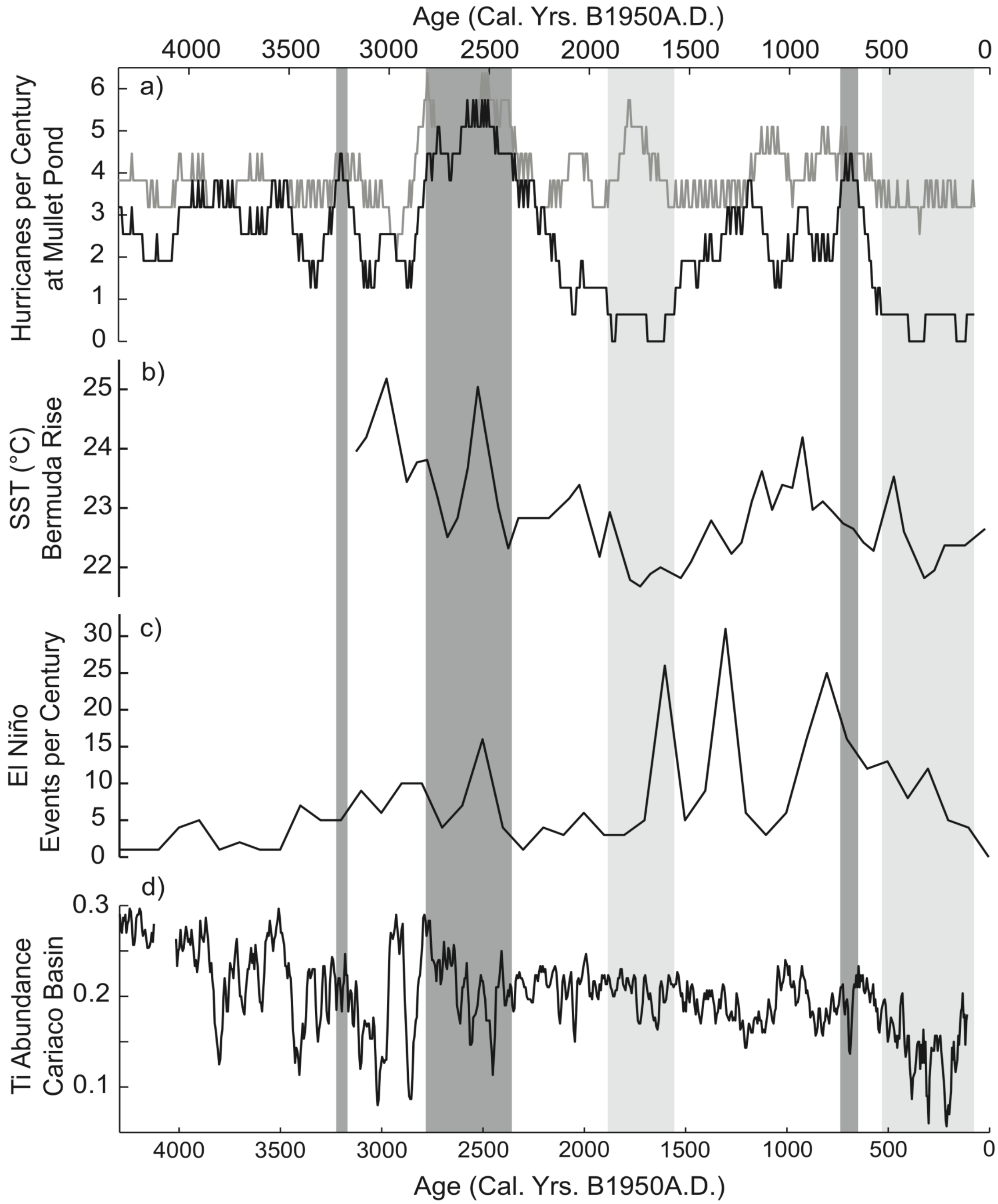

Figure 8 - Panel (a) is the time series of hurricane frequency at Mullet Pond from 4294 to 21 cal. yrs. $B_{1950A.D.}$. The gray curve is the LT time series and the black curve is the HT time series. The darker gray shaded portion highlights a period with storm frequency that exceeded the 90th percentile of what would be expected by chance. The period shaded in light gray saw fewer hurricanes with storm frequency in the bottom 10th percentile of what would be expected by chance. Panel (b) is an estimate of annual mean SST at the Bermuda Rise (33°41.6'N, 57°36.7'W) based on ∂O^{18} values of the foraminifera *G. ruber* (Keigwin 1996). Panel (c) is an estimate of the number of El Niño events per century as recorded in the color intensity of a sediment core taken from the Ecuadorian lake Laguna Pallacacocha (2°46'S, 79°14'W) (Moy et al. 2002). Panel (d) is the time series of Titanium (Ti) abundance in a sediment core taken from ODP Site 1002 (10°42'N, 65°10'W) in the anoxic Cariaco Basin off of Venezuela. Ti concentrations at the site are thought to document terrestrial runoff, which in turn may reflect changes in the mean position of the Intertropical Convergence Zone (ITCZ). Higher (lower) Ti abundance may correspond with increased (decreased) northward displacement of the ITCZ from the equator (Haug et al. 2001).

recognized varieties of ENSO behavior may account for some of the differences between the Mullet Pond and Vieques paleohurricane records. The concomitance of changes in the frequency of EPW and CPW events on long timescales may explain why hurricane activity at the two sites is seemingly out of phase. For example, if the frequency of CPW events increased in concert with EPW events around 1000 cal. yrs. B.P., then the long-term frequency of landfalls in eastern North America may have increased even while activity in the Caribbean declined around that time.

While the ENSO may have driven some of the variability in Atlantic hurricane activity over the last 5000 years, even a permanent El Niño-like state could not on its own account for the extent and duration of the least active portions of the Vieques record (Woodruff et al. 2008a). Comparing storm frequency at Mullet Pond with a Titanium-based terrestrial runoff record from the Cariaco Basin (Figure 8d) suggests that Gulf hurricane activity tended to be higher while northward displacement of the ITCZ in the Atlantic was greatest (Haug et al. 2001). Similarly, changes in Caribbean major hurricane frequency occurred together with changes in equatorial West African rainfall (Donnelly and Woodruff 2007), which is largely controlled by the position of the ITCZ (Nguetsop et al. 2004). Since the ENSO and the mean latitude of the Atlantic ITCZ are thought to be dynamically linked (Curtis and Hastenrath 1995, Saravanan and Chang 2000, Haug et al. 2001, Chiang et al. 2002), constructive interference between the two may modulate how favorable conditions are for Atlantic tropical cyclones on many timescales. For example, an increase in El Niño frequency concurrent with equatorward drift of the ITCZ could drive a suite of thermodynamic and circulation changes in the tropical North Atlantic including decreasing SSTs, latent heat flux, low-level convergence and vorticity and increasing sea level pressure, static stability and vertical wind shear. All of these changes would cooperate to make conditions less favorable for the formation and development of North Atlantic hurricanes in the Main Development Region (Gray 1968). This mechanism of cooperative interference is best described by the Atlantic Meridional Mode (AMM), which has been useful in explaining high-frequency variability in the instrumental record of Atlantic hurricanes (Vimont and Kossin 2007). The collusion of storm-relevant variables on longer timescales in the North Atlantic may also account for the significant, centennial and millennial-scale variability in late-Holocene hurricane climate that is evidenced by a growing number of paleohurricane records.

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