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Notes

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ABSTRACT

Hurricane magnitude and frequency have been linked to numerous mechanisms, including the steady rise in annual sea-surface temperatures, El Niño–Southern Oscillation (ENSO) variations, and atmospheric changes. In order to better understand those factors that control hurricane magnitude and frequency, a long-term record spanning the entire Gulf of Mexico coast is needed. Here we present a detailed record from ca. 5300–900 yr B.P. of past intense hurricane impacts for cores collected from Laguna Madre, Texas, United States. Relative storm intensities were calculated for each event, and the average intense storm impact probability for south Texas was determined to be ~0.46% (annual landfall probability). Previous field studies in Western Lake, Florida, and Lake Shelby, Alabama, reveal similar probability intense hurricane strikes of ~0.39%. Although high-frequency oscillations between warm and dry and cool and wet climate conditions have occurred in Texas through the late Holocene, there has been no notable variation in intense storm impacts across the northwestern Gulf of Mexico coast during this time interval, implying no direct link between these changing climate conditions and annual hurricane impact probability. In addition, there have been no significant differences in the landfall probabilities of storms between the eastern and western Gulf of Mexico during the late Holocene, suggesting that storm steering mechanisms have not varied during this time.

INTRODUCTION

Several studies have attempted to study tropical storm frequency and magnitude trends from storm overwash sediment records (Liu and Fearn, 1993,2000a, 2000b; Donnelly et al., 2001a, 2001b, 2004; Donnelly and Woodruff, 2007; Woodruff et al., 2008; Mann et al., 2009; see Appendix DR1 in the GSA Data Repository[1]). Although these studies have provided valuable data for the Atlantic Ocean and eastern Gulf of Mexico (Florida and Alabama), none has targeted the northwestern Gulf of Mexico. In Texas, Laguna Madre (Fig. 1) was assumed to be the most ideal location for paleotempestological studies, because it is an elongate water body behind the narrow, low-elevation barrier (<2 m) of South Padre Island (Fig. 1). We consider our record to be directly comparable to other paleotempestological studies because all are thought to record intense hurricane activity. This extreme western location was also selected in order to quantify phase relationships between intense hurricanes impacts between the eastern and western Gulf of Mexico. In addition, extensive Texas climate records (Appendix DR2) allow relationships between high-frequency climate cycles and intense storm impacts to be determined.

[1]GSA Data Repository item 2010149, Appendices DR1–DR6 (methods, archival data, calculating $\langle h_b \rangle$, error quantification, and radiocarbon reservoir effect), is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

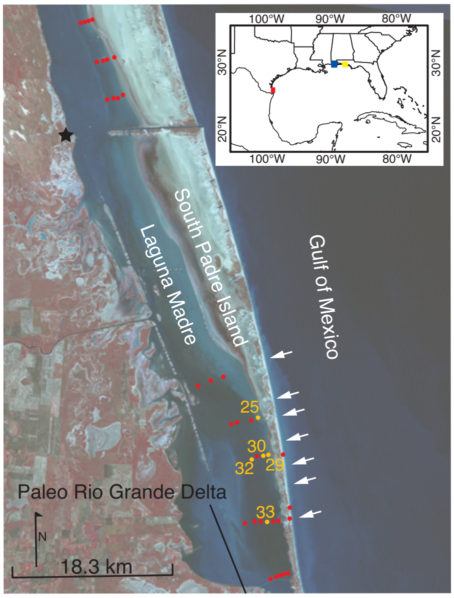

Figure 1. Study area and core locations. Map of Laguna Madre (LM), Texas (base map from U.S. Geological Survey National Map viewer [http://nmviewogc.cr.usgs.gov/viewer.htm]). Core locations are indicated by red dots (all cores collected) and yellow dots (cores used for this study). Inset map indicates this study (LM, red box), and previous studies in Lake Shelby, Alabama (Liu and Fearn, 1993) (blue box), and Western Lake, Florida (Liu and Fearn, 2000a) (yellow box). Note extensive breaching and overwash features, indicated by white arrows on South Padre Island. Port Mansfield, where Hurricane Allen's surge was measured in 1980, is identified by black star.

Of the hurricanes in which the eye passed directly over South Padre Island during historic time (A.D. 1854–2007), only Hurricane Allen (1980) has been classified as a Category 3 or higher storm (Blake et al., 2007) (~0.65% annual landfall probability). Modern intense storm impacts for Lake Shelby, Alabama, are estimated to be ~0.3% (Elsner et al., 2008), while no Category 4 or higher storms affected Western, Lake, Florida, during historic time (Liu and Fearn, 2000a).

Subsidence of the Rio Grande delta plain (Fig. 1) resulted in the formation of Laguna Madre (Morton, 1994), and likely was especially rapid ~5000 yr ago, locally creating ample accommodation space for preservation of storm washover deposits. During the late Holocene, the Rio Grande Delta became inundated and reworked and South Padre Island began forming. It is a narrow and thin transgressive barrier, with an average width of 3.8 km and average height of 3.75 m (Morton and Price, 1987; Morton and McGowen, 1980). Today, because of a restricted tidal exchange, astronomical tides are extremely low in Laguna Madre (~30 cm) (Rusnak, 1960). Our radiocarbon data suggest that South Padre Island has been relatively stable for at least the past several millennia.

METHODS FOR IDENTIFYING PALEOHURRICANES

We collected 37 sediment cores along 8 transects within Laguna Madre (Fig. 1). Within intervals where radiocarbon dates were taken (Fig. 2; Appendix DR2), grain size analyses were performed every 1 cm. Samples were taken every 5 cm in sections where no radiocarbon dates were taken. These latter intervals also coincided with environments not interpreted to be washover clay couplets. Although a radiocarbon reservoir has been found along some of the bays in Texas (Milliken et al., 2008), the extremely limited exchange between Laguna Madre, fluvial systems, and the Gulf of Mexico suggests a negligible effect in Laguna Madre.

RESULTS

Not all of the cores yielded a record of storm landfall probability, due mainly to bioturbation. Our initial sampling strategy (core transects) assumed that some cores would be located too close to the barrier and therefore would sample amalgamated storm deposits, others would

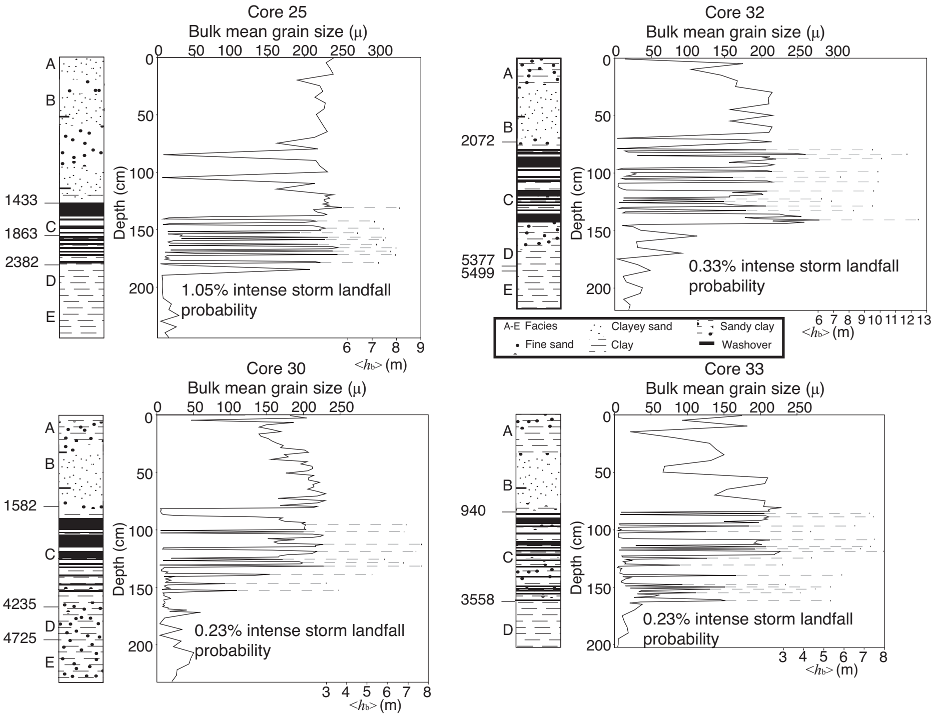

Figure 2. Grain size and relative storm intensities for cores 25, 30, 32, and 33 from Laguna Madre, Texas. Lithologies, bulk mean grain size, and predicted <h_b> (water flow depth over barrier; Appendix DR3; see footnote 1) values (dashed lines) are plotted for each core. Washover deposits are indicated by solid black in lithologic description, and coincide with bulk mean grain size increases. Facies are identified by letters to left of lithologic description. Age intervals are calibrated radiocarbon dates from mollusc shells within bay sediments (Appendix DR2). Note similar probabilities of intense hurricane impacts between cores.

be too distal to sample storm deposits, and not every transect would occur where there was adequate accommodation for deposition and preservation of washover deposits. However, four cores from two transects yielded a distinct record and enough carbonate material for radiocarbon age dating to constrain the timing of hurricane overwash. Cores 25, 30, 32, and 33 (Figs. 1 and 2) sampled ~20 cm of organic-rich, bioturbated clays (unit A), overlying ~60 cm of clayey sand or sandy clay (unit B), then ~100 cm of light gray bay clay interbedded with fine sand units (unit C), all deposited over gray bay clays (unit D) and highly oxidized fluvial plain clays (unit E). Unit A represents the biologically active component of the modern system. Living infauna and plants were found to a depth of ~20 cm in all cores. Unit B represents ~1000–1500 yr of highly bioturbated deposits. Other than hurricane impacts (overwash processes), no known mechanism can explain fine sand deposition within Laguna Madre in unit C. Gray clay layers likely represent fair-weather quiescent lagoon deposition. Radiocarbon dating of indigenous bay fauna within individual clay beds was used to constrain the time interval over which discrete storm beds were deposited (Fig. 2; Appendix DR2).

Modern Analogue

From historic records, ~13 hurricanes passed within 65 km of the South Padre Island area from A.D. 1854 to 2007 (Blake et al., 2007). However, we find evidence of only one modern discrete washover event recorded in our core data. Core 29 contained ~30 cm of a fine sand washover unit sharply overlying a clayey sand unit. ^{137}Cs measurements yielded a concentration spike (indicating A.D. 1963 ± 2) ~5 cm below the base of the washover unit (Appendix DR2). This deposit was thus associated with Hurricane Allen (1980), which was a Category 3 storm, due to the proximity of this core to the known hurricane track, the age of the deposit, and the fact that no hurricanes passed within 65 km of South Padre Island between 1981 and 2007 (Blake et al., 2007).

RELATATIVE STORM INTENSITIES

A method for predicting flow depth of water over a barrier (<h_b>) from extreme hurricane flooding events has recently been established (Woodruff et al., 2008) (Appendix DR3). This method allows relative comparisons of storm intensities between discrete storm deposits. Because Hurricane Allen was the only modern storm known to have left a deposit in Laguna Madre, and it was the only intense storm to impact South Padre Island during historic time, this event was used to establish a modern analogue for predicted <h_b> values (Appendix DR2). Wave heights over the barrier were calculated to be 6.6 m for Hurricane Allen. The measured surges associated with this storm were as much as 3.7 m at Port Mansfield, Texas (Fig. 1) (Roth, 2000), although the highest surges occurred in uninhabited regions of the coast and thus were not measured. Woodruff et al. (2008) cautioned that predicted <h_b> values could overestimate exact storm surges from modern deposits. However, we still consider this method to be the best quantitative means of deriving relative differences in storm intensity within a given location. Thus, to constrain high-intensity storms, we use the predicted <h_b> values from Hurricane Allen as a baseline. For South Padre Island, <h_b> values were calculated for each hurricane event from the four cores (Fig. 2). Our data yield <h_b> values between 3 and 13 m, but only inundation heights ≥6.6 m were classified as intense storms. Intense storm-predicted values of <h_b> ranged from 7.1 to 8.1 m in core 25, from 6.8 to 7.7 m in core 30, from 6.9 to 12.4 m in core 32, and from 6.8 to 7.9 m in core 33 (Fig. 2; Appendix DR4). South Padre Island has extremely uniform sand grain size, so overwash events recorded in our cores reflect the maximum grain sizes available for transport from the barrier into the lagoon. This explains the observed lack of lateral sorting in washover events (Fig. 2). By spacing cores large distances apart, using an advective model to calculate relative storm intensity seems appropriate due to a wide range of sample distances from the barrier (Fig. 1).

HOLOCENE GULF OF MEXICO INTENSE HURRICANE ACTIVITY

The storm overwash record from the 4 cores spans 20 km of backbarrier shoreline (Fig. 1) and shows little variability in intense hurricane landfall probabilities for the time interval 5377–940 yr B.P. Six hurricane events are recorded from 4235–1582 yr B.P. (0.23% landfall probability) in core 30, 10 from 2382–1433 yr B.P. (1.05% landfall probability) in core 25, 6 from 3558–940 yr B.P. (0.23% landfall probability) in core 33, and 11 from 5377–2072 yr B.P. (0.33% landfall probability) in core 32 (Fig. 2; Appendices DR2 and DR5). The slightly higher landfall probability observed in core 25 could be due to its more northern location that perhaps recorded storms not affecting the more southern cores. Due to low sedimentation rates in Laguna Madre, it is possible that one storm bed could potentially represent multiple events, although the similar hurricane counts between cores separated by tens of kilometers suggests that this effect might be negligible. Due to lagoon morphology, there is a range in the observed age intervals. However, these time intervals overlap significantly, and all yield consistently similar landfall probabilities. Therefore, an average landfall probability between ~5300 and 900 yr B.P. within the 20-km-wide study area of ~0.46% was calculated from these four cores (Appendix DR2).

A recent study concluded that 12 hurricanes likely of Category 4 or higher intensity struck Western Lake, Florida, from 3543–492 yr B.P. (~0.39% landfall probability) (Liu and Fearn, 2000a; Appendix DR1) (Fig. 3). In coastal Alabama, Lake Shelby has yielded evidence of 11 hurricane impacts of Category 4 or higher from 3500–700 yr B.P. (~0.39% landfall probability) (Liu and Fearn, 2000b) (Fig. 3). A recent modeling study (Elsner et al., 2008) estimated a modern landfall probability of intense storms for this area to be ~0.3%. In the western Gulf of Mexico, we show average landfall probabilities from ca. 5300–900 yr B.P. of ~0.46% (Figs. 2 and 3). Our average landfall probabilities are possibly slightly higher due to sampling a longer time interval and wider geographic area. However, these remarkably similar landfall probabilities shed light on a regional hurricane record along the Gulf of Mexico coast.

In addition, our findings seem to correlate well with two recent paleotempestological studies in the Caribbean and North America. A 5000 yr hurricane record from Laguna Playa Grande in Vieques, Puerto Rico (Fig. 3), showed that there were intense hurricanes from ca. 4400 to 3600 yr B.P., 2500 to 1000 yr B.P., and from 250 yr B.P. to present (Donnelly and Woodruff, 2007). During historic time, hurricanes affecting Laguna Playa Grande generally have been steered toward the Atlantic, although some have entered the Gulf of Mexico. The hurricane record presented in this study from Laguna Madre, Texas, included three overlapping intervals similar to Laguna Playa Grande: ca. 4235–1582 yr B.P., 2382–1433 yr B.P., and 3558–940 yr B.P. Recent work from North America compiled several sedimentary records and created statistical models yielding evidence for a peak in Atlantic hurricane activity around A.D. 1000, followed by a period of inactivity (Mann et al., 2009). Aside from the modern deposit from Hurricane Allen, we see little evidence of discrete storm bed preservation from ca. 1000 yr B.P. to present.

The geological record becomes better constrained with the addition of properly located study areas within the Gulf of Mexico and Caribbean and the analysis of robust data sets. We consider our data set to be accurate and robust because of the regularly spaced distribution of cores in the area. In addition, our study area encompasses ~20 km of coastline and shows little variability in paleohurricane landfall probabilities. Our data set suggests intervals of intense hurricane impacts remarkably similar to other paleotempestological sites around the Gulf Coast and Caribbean separated by hundreds of kilometers (Fig. 3; Appendix DR2).

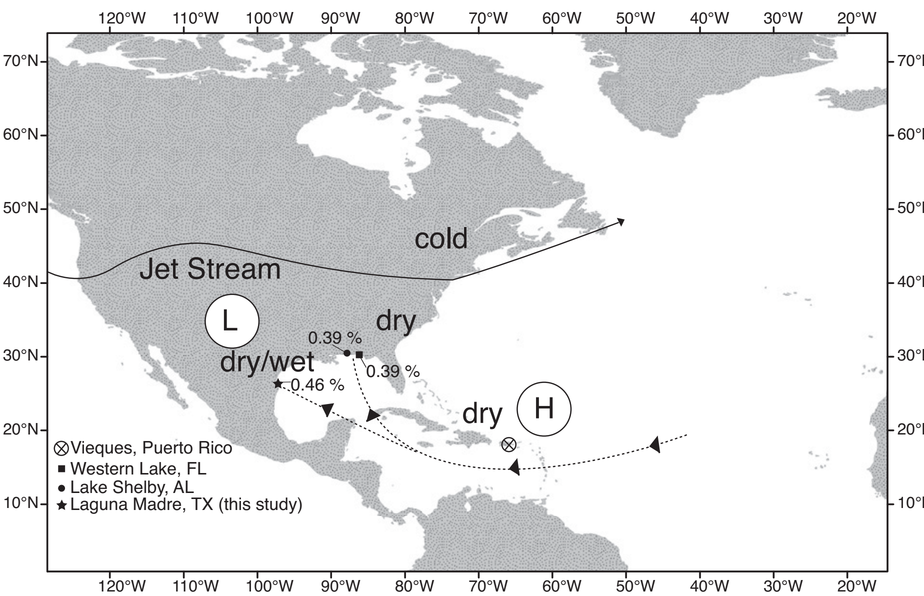

Figure 3. Gulf of Mexico intense hurricane landfall probability comparison for late Holocene. Intense hurricane landfall probabilities for Lake Shelby, Alabama (Liu and Fearn, 2000b), Western Lake, Florida (Liu and Fearn, 2000a), and Laguna Madre, Texas (this study). Average landfall probability between four cores from Laguna Madre are calculated to be ~0.46%. Note similar probabilities for all three sites, indicating regional signature. Location of Vieques, Puerto Rico, indicates recent study (Donnelly and Woodruff, 2007) where intense hurricane activity occurred from ca. 4400 to 3600 yr B.P., 2500 to 1000 yr B.P., and 250 yr B.P. to present. These time intervals overlap with all three studies. Note locations of the jet stream with associated thermal low (L), and the Bermuda High (H) (Forman et al., 1995). Dry conditions near southeastern North America (Forman et al., 1995; Liu and Fearn, 2000a), and shifting dry and/or wet conditions over Texas are also represented. Black dashed line represents hypothetical intense hurricane tracks under these conditions.

INTENSE HURRICANE IMPACT CLIMATE FORCINGS

A recent study suggests that warmer sea-surface temperatures (SST) in the Atlantic were not the main mechanism for increased intense hurricane activity for the past several millennia at Laguna Playa Grande (Donnelly and Woodruff, 2007), although SST change cannot be completely ruled out. Rather, intervals of frequent intense hurricane impacts (i.e., ca. 4400–3600 yr B.P., 2500–1000 yr B.P., 250 yr B.P. to present) can be correlated with periods of fewer El Niño events and increased precipitation in tropical Africa. It has also been suggested that the jet stream and the Bermuda High have shifted south and southwest, respectively, since the mid-Holocene Thermal Maximum (Fig. 3) (Forman et al., 1995). This claim is bolstered by the fact that oxygen isotopic records from Lake Miragone, Haiti, suggest an abrupt shift toward dry conditions in the late Holocene (Hodell et al., 1991). A shift in circulation patterns likely explains the observed change in the probabilities of impacts in northwestern Florida (Western Lake) and coastal Alabama (Lake Shelby) (Liu and Fearn, 2000a) (Fig. 3).

Paleoclimate data spanning much of Texas show oscillations between warm and dry and cool and wet conditions in the late Holocene (Fraticelli, 2003; Appendix DR2). It has been hypothesized that high pressure (associated with westward-flowing cool, wet air masses) would effectively steer storms away from an area (Liu and Fearn, 2000a). Although this likely explains intense hurricanes being steered toward the Atlantic Ocean (Liu and Fearn, 2000a), our data indicate that despite high-frequency (lasting ~500–1000 yr) climate oscillations, there has been no significant change in storm landfall probability over this time interval for the Gulf of Mexico. Furthermore, there is no evidence of any clear out-of-phase relationship that would indicate a direct correlation between climate and storm steering mechanisms for this area.

CONCLUSIONS

We estimated relative storm intensities for each event from a detailed record of past intense hurricane impacts from ca. 5300–900 yr B.P. from Laguna Madre, Texas. Average intense storm impact probability for south Texas was determined to be ~0.46%. By combining our results with previous field studies from Western Lake, Florida, and Lake Shelby, Alabama, that provide a record of intense storm impacts from the eastern Gulf of Mexico, the intense hurricane impact history of the Gulf of Mexico for the Holocene can be constrained. These studies reveal similar probability intense hurricane strikes of ~0.39%. Current rates of intense hurricane impacts for Western Lake, Florida, Lake Shelby, Alabama, and Laguna Madre, Texas, do not seem unprecedented when compared to intense strikes over the past 5000 yr. In Texas, the probability of intense storm impacts does not appear to have varied during the late Holocene, although this was a period of high-frequency oscillations between cool and wet, and warm and dry climate conditions. Similar probabilities in high-intensity hurricane strikes for the eastern and western Gulf of Mexico do not show any clear-cut out-of-phase relationship that would enlighten us as to those climate controls on storm pathways. Thus, in the northern Gulf of Mexico, there have been no significant variations in storm impact probabilities and/or storm steering mechanisms from ca. 5300–900 yr B.P.

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