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Reconstruction of Prehistoric Landfall Frequencies of Catastrophic Hurricanes in Northwestern Florida from Lake Sediment Records

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Sediment cores from Western Lake provide a 7000-yr record of coastal environmental changes and catastrophic hurricane landfalls along the Gulf Coast of the Florida Panhandle. Using Hurricane Opal as a modern analog, we infer that overwash sand layers occurring near the center of the lake were caused by catastrophic hurricanes of category 4 or 5 intensity. Few catastrophic hurricanes struck the Western Lake area during two quiescent periods 3400–5000 and 0–1000 ^{14}C yr B.P. The landfall probabilities increased dramatically to ca. 0.5% per yr during an "hyperactive" period from 1000–3400 ^{14}C yr B.P., especially in the first millennium A.D. The millennial-scale variability in catastrophic hurricane landfalls along the Gulf Coast is probably controlled by shifts in the position of the jet stream and the Bermuda High.

Key Words: **hurricanes; paleotempestology; coastal lakes; lake sediments; overwash events; storm deposits; climate variability; Gulf of Mexico.**

INTRODUCTION

The observational record of hurricane activities in North America is essentially confined to the past 130 yr (Neumann *et al.,* 1987; Ludlam, 1963). Examination of this historical record reveals significant interannual and interdecadal variability in hurricane activities, which can be related to regional to global-scale climatic phenomena such as Sub-Saharan drought and El Nino–Southern Oscillation (ENSO) events (Gray, 1990; Landsea *et al.,* 1996; Elsner and Kara, 1999). Due to the brevity of the historical record, it is unknown whether such variability occurs at longer timescales of centuries to millennia. This question can be answered by means of paleotempestology, a new field that studies past hurricane activities by means of geological proxy techniques (Liu, 2000). A pioneer study from Lake Shelby, Alabama, demonstrated that overwash sand layers preserved in the sediments of coastal lakes can provide a proxy record of catastrophic hurricane strikes during the late Holocene (Liu and Fearn, 1993). Lake Shelby is the only available millennial record of catastrophic hurricane landfalls for the Gulf of Mexico coast. Here we present a new, high-resolution record that spans the past 7000 yr from the Gulf Coast of northwestern Florida.

THE STUDY SITE

Western Lake (30° 19′ 31″ N, 86° 09′ 12″ W) is separated from the Gulf of Mexico by a 150- to 200-m-wide barrier beach (Fig. 1). At the back of the beach, well-developed sand dunes form a continuous ridge about 6.2 m high, with individual dunes rising up to 7.7–9.3 m above sea level. The lake maintains a restricted connection to the Gulf through an intermittent tidal outlet about 1 km to the west. In July 1997, salinity of the lake water ranged from 5.9 ppt near the tidal channel to 2.5 ppt near the center. The lake has a flat bottom with a maximum water depth of ca. 3.3 m.

RECENT HURRICANE IMPACTS

Western Lake was severely impacted by Hurricane Opal on October 4, 1995, when this high category 3 hurricane made landfall near Pensacola, Florida, about 75 km to the west of the lake. The 40 m/s wind and nearly 6- m-high storm surge caused significant property damage and beach and dune erosion. Although the dune ridges were not overwashed, sand was introduced into the lake by saltwater invading through the tidal channel from the west (John Bente, Grayton Beach State Park biologist, pers. commun., 1996) (Fig. 1). Previously, Western Lake was directly struck by three other hurricanes of category 3 intensity—in 1917, 1936, and 1975 (Hurricane Eloise) (Neumann *et al.,* 1987). Eloise, the strongest of these three, made landfall closer to the site than did Opal. However, the storm surge (maximum 4.9 m) was lower than that of Opal's, and it

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TABLE 1
List of Radiocarbon Dates from Western Lake

Core No.	Depth (cm)	^{14}C age (yr B.P.)	Lab no.	Material
1	36–46	1350 ± 80	Beta-61600	Organic lake mud
1	135–145	3310 ± 80	Beta-60240	Organic lake mud
1	239–249	3870 ± 70	Beta-61601	Organic lake mud
1	316–326	4930 ± 80	Beta-60241	Organic lake mud
1	418–428	6820 ± 120	Beta-60242	Organic lake mud
9	15–16[a]	1170 ± 50	Beta-099787	Organic lake mud
9	36–37[a]	1210 ± 50	Beta-099788	Organic lake mud
9	53–54[a]	1320 ± 50	Beta-099789	Organic lake mud
9	61–62[a]	1410 ± 50	Beta-099790	Organic lake mud
9	69–70[a]	1850 ± 50	Beta-099791	Organic lake mud
14	19–20[a]	1170 ± 40	Beta-103030	Organic lake mud

[a] AMS date.

caused only limited landward sand transport by the invading floodwater (Morton, 1976). Although no strike by a category 4 or 5 hurricane or any overwash event has occurred at Western Lake during the historic period, such catastrophic hurricanes were likely to have struck during prehistoric times, as suggested by the presence of what appears to be two lobes of overwash sand and dunes of indeterminate age on the southeastern shore of the lake (Fig. 1).

RATIONALE AND METHODS

Coastal lakes like Western Lake or Lake Shelby are subject to overwash processes due to strikes by catastrophic hurricanes. Overwash occurs when the storm surge caused by a landfalling hurricane exceeds the height of the sand barrier (e.g., barrier beach or dune ridges). As a result of wave activity, sand is eroded from the overwashed beach or dune fields into the lake, forming an overwash fan that spreads out in the form of a sand layer on top of the finer, organic-rich sediment that normally accumulates in small, sheltered lake basins. This sand layer is thicker near the lake shore and thinner toward the center. The horizontal extent of the sand layer is affected by many complicating factors, such as hurricane intensity and storm surge height, coastal configuration, lake morphometry, abundance of sand supply, tidal height at time of landfall, angle of hurricane landfall and wind direction, and timing and duration of landfall. Assuming that the geomorphic setting remains the same for any given lake and that hurricane landfall conditions (e.g., timing, duration, angle of approach) occur randomly over time, we may infer that stronger hurricanes tend to result in higher storm surges. High storm surges, in turn, would tend to produce a thicker and more widespread overwash sand layer (Liu and Fearn, 1993, 2000). We illustrate our point with a hypothetical case in which a coastal lake was subjected to overwash events caused by land-

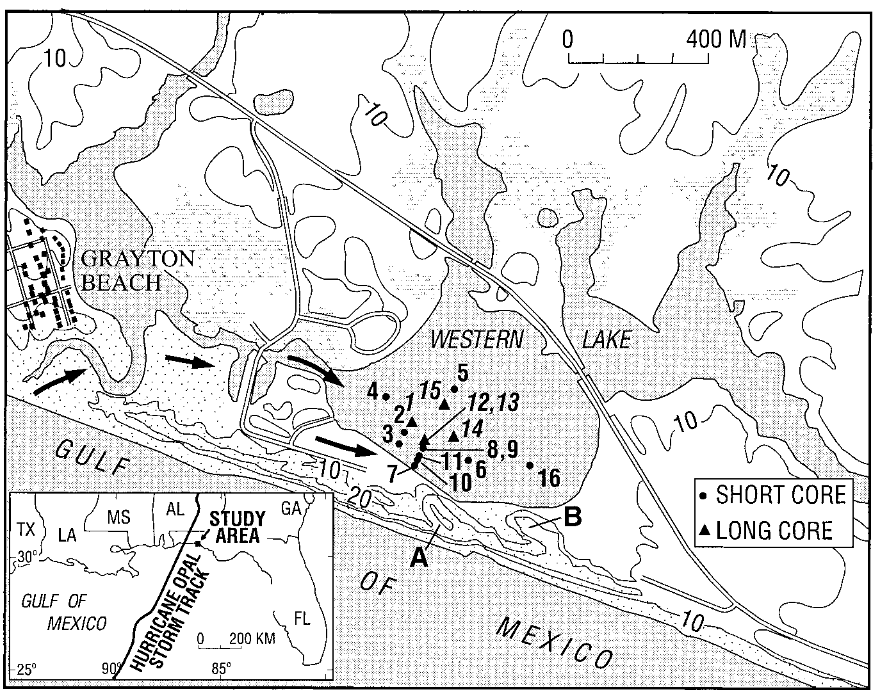

FIG. 1. Geomorphic setting of Western Lake showing location of 16 sediment cores used in the stratigraphic study. Contour intervals are in meters. Arrows show direction of saltwater invasion and sand transport caused by Hurricane Opal's storm surge. Two lobes of possible washover deposits and associated sand dunes on the south shore are marked A and B. (Inset) Location of Western Lake in relation to the path of Hurricane Opal. States are identified as Florida (FL), Georgia (GA), Alabama (AL), Mississippi (MS), Louisiana (LA), and Texas (TX).

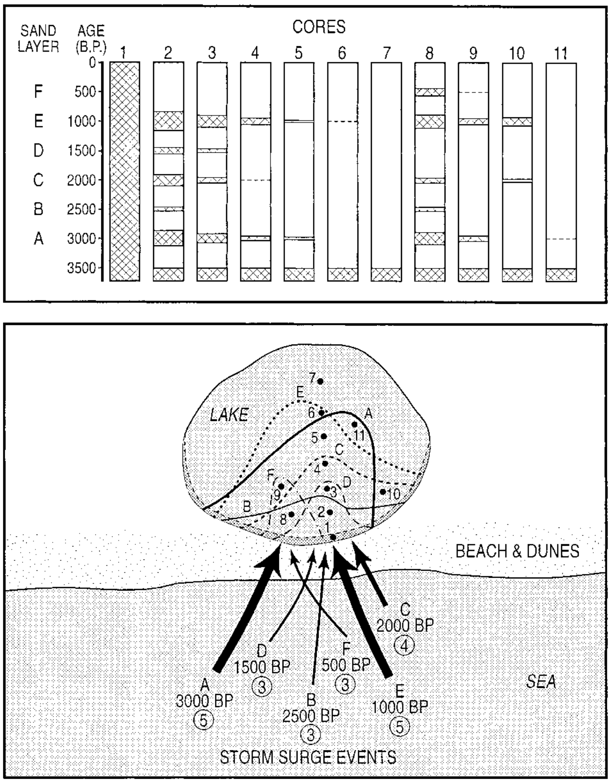

FIG. 2. Hypothetical pattern of overwash sand deposition in a coastal lake situated behind a barrier beach and sand dunes (bottom). Intense hurricanes are indicated by arrows A–E. Thicknesses of the arrows are proportional to the intensity of the hurricanes according to the Saffir-Simpson scale, the latter also designated by the circled number associated with each arrow (e.g., circled 3, category 3 hurricane). Horizontal extent of each overwash sand fan is denoted by solid, dashed, or dotted lines in the lake (labeled A–E corresponding to the six hurricane strikes). Numbered black dots (1–11) represent cores taken from different parts of the lake. The number and thickness of overwash sand layers vary from one core to another (top) as a function of the varying horizontal extents and thicknesses of the overwash sand fans. See text for further explanation.

falling hurricanes of various intensities six times (A–E) during the past 3000 yr (Fig. 2). Each overwash event resulted in the deposition of a sand layer whose size and shape may vary but is generally proportional to the intensity of the hurricane and the overwash event. According to this model, cores taken closer to shore (e.g., cores 2, 3, 4, 8, 9) should contain more and thicker sand layers than cores taken farther away (e.g., cores 5, 6, 7, 11). However, cores taken next to the shoreline (e.g., core 1) likely would not resolve individual overwash events, although they probably would consist entirely of sand. Cores taken near the lake center (cores 5, 6) should contain the fewest and thinnest sand layers, because they record the impacts of only the strongest hurricanes (A, E). Cores taken at a great distance from shore (e.g., core 7) could lie beyond the limits of all sand fans and thus contain no sand layers. As the spatial extent of the sand layers varies from one event to another, cores taken from different parts of the lake, even though they may be similar distances from the shoreline, could contain different numbers of sand layers and record different events (e.g., compare cores 2, 8, 10; cores 3 and 9; cores 5 and 11). Thus a suite of cores taken from different sites is vital for producing a complete record of past hurricane landfalls. With this understanding, the frequency, extent, thickness, and chronology of the sand layers could then be used as a proxy for reconstructing the history of hurricane strikes, provided that the sedimentological "fingerprints" of a modern hurricane of known intensity and geomorphic impact can be used as a control for comparison (Liu and Fearn, 1993, 2000).

Sixteen cores were collected from Western Lake to provide an adequate sampling network for correlating storm layers (Fig. 1). We used a piston corer consisting of a 1.5-m-long detachable clear-PVC tube fitted with a stainless steel cutting shoe at the end. Upon retrieval from the lake, the coring tube containing the sediment was held upright and sealed with rubber stoppers at both ends to minimize disturbance during transportation. Cores 1–6 were collected in 1992 prior to Opal, and cores 7–16 were collected in 1996 after Opal. Core 1, collected ca. 100 m from the south shore, was studied intensively to produce a millennial history of catastrophic hurricane landfalls for Western Lake.

The cores were sampled continuously at 1-cm intervals. Samples were heated at 105° and 550°C to determine their water and organic matter contents, respectively (Dean, 1974). All age estimates for the sediment stratigraphies are based on linear interpolation between radiocarbon dates (Table 1).

SEDIMENT STRATIGRAPHIES

Of the 10 cores taken after Opal, only core 11 contains a distinct sand layer that may be attributed to the Opal strike (Fig. 3). This short core was taken at a site only 20 m away from the south shore (Fig. 1) at a water depth of 2.5 m. The sand layer is 1.5-cm-thick and immediately overlies organic lake mud that contains 5–10% organic matter and little or no sand (Fig. 4). The layer is composed of coarse, white sand similar to that found on the beaches and low dunes immediately fringing the lake. Since Opal's storm surge did not overwash the dune ridge, the sand must have been deposited by floodwater that invaded through the tidal channel and eroded the base of the dunes and beaches along the south shore (Fig. 1).

Stratigraphic data from other cores confirm that the Opal sand layer is confined to a narrow belt along the south shore. Short cores (cores 7 and 10) taken in shallower water and closer to shore than core 11 contain only sand. Apparently the storm deposits from Opal and previous hurricanes are too thick at these sites and the water is too shallow for organic lake mud to accumulate. Cores taken farther away from the south shore (cores 8–9, 12–16) contain predominantly organic lake mud with intercalating sand layers, but no sand layer occurs at the core top that can be attributed to Opal (Fig. 3).

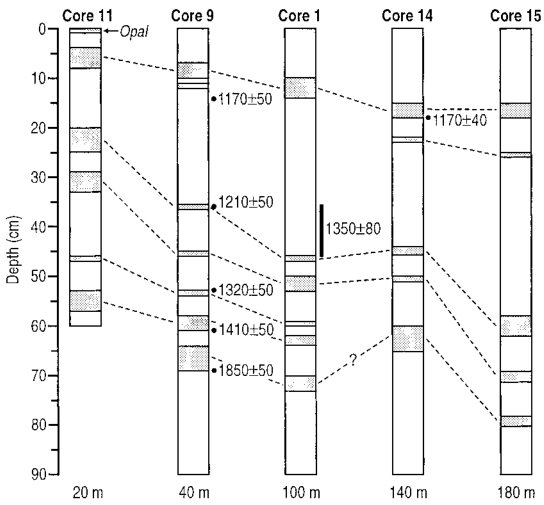

FIG. 3. Sediment stratigraphy for cores 11, 9, 1, 14, and 15, arranged from left to right according to increasing distance from the south shore (bottom, not to scale). The Hurricane Opal sand layer (arrow) is present only in core 11, a core taken nearest to shore. Radiocarbon dates are uncalibrated ^{14}C ages in years before present (yr B.P.).

The pre-Opal sand layers in these cores (e.g., cores 9, 1, 14, 15) range from a few millimeters to over 10 cm in thickness, but most are a few centimeters thick (Fig. 3). They also vary in distinctness and in texture. The more prominent sand layers are typically composed of coarse, white sand and have sharp contacts with the organic sediments above and below (Fig. 5). For coarse sand to be transported that far toward the lake center, these older sand layers must have been deposited by overwash processes when storm waves overtopped the sand dunes during past strikes by catastrophic hurricanes more intense than Opal. Generally, sand layers are thicker and more numerous in cores taken close to shore (cores 11, 9), and are thinner and fewer in number in cores taken farthest away from shore (cores 14, 15). This pattern occurs because only the highest storm surges, presumably caused by hurricanes of category 4 or, more likely, category 5 intensity can spread the coarse sand far away from the overwashed dunes on the south shore. The major sand layers can be broadly correlated among these cores (Fig. 3).

HOLOCENE COASTAL ENVIRONMENTAL CHANGES

Core 1 was retrieved at a site 100 m away from the south shore. Although the core was taken before the Opal strike and therefore does not contain any sand layer at the top, the coring site would have been too far to be reached by the Opal sand layer. The sediment stratigraphy consists of 4.3 m of organic lake mud overlying almost 2 m of basal sand (Fig. 6).

The sediment stratigraphy of core 1 suggests that the Western Lake basin was formed shortly after 7000 ^{14}C yr B.P. as a result of the postglacial transgression. Between ca. 5000 and 7000 ^{14}C yr B.P., the sediment changed from sandy clay to organic clay with increasing organic contents upcore, reflecting the progressive development toward a stable, productive lake environment. The sandy sediments and sand layers occurring in this interval were probably due to the opening and closure of the sand barrier that subsequently formed the modern beach and dune system that separates Western Lake from the Gulf. These sand layers cannot be ascribed to hurricane events, because the limnology and geomorphic setting (e.g., tidal connection, beach and dune ridge height, basin morphometry) of the lake basin might have been different during this initial phase of lake development.

After ca. 5000 ^{14}C yr B.P., the water and organic contents of the organic sediments have remained fairly uniform at about 60–70 and 10–15%, respectively, except for the sand layers. This result suggests that the modern lake environment was established 5000 yr ago and has remained essentially unchanged since then. Sediments from completely freshwater (salinity <0.5 ppt) coastal lakes situated in similar topographic settings to Western Lake but with no tidal connection to the Gulf (e.g., Campbell Lake, northwestern Florida; Little Lake, Alabama) typically contain 40–50% organic matter. However, sediments from brackish-water coastal lakes or lagoons with

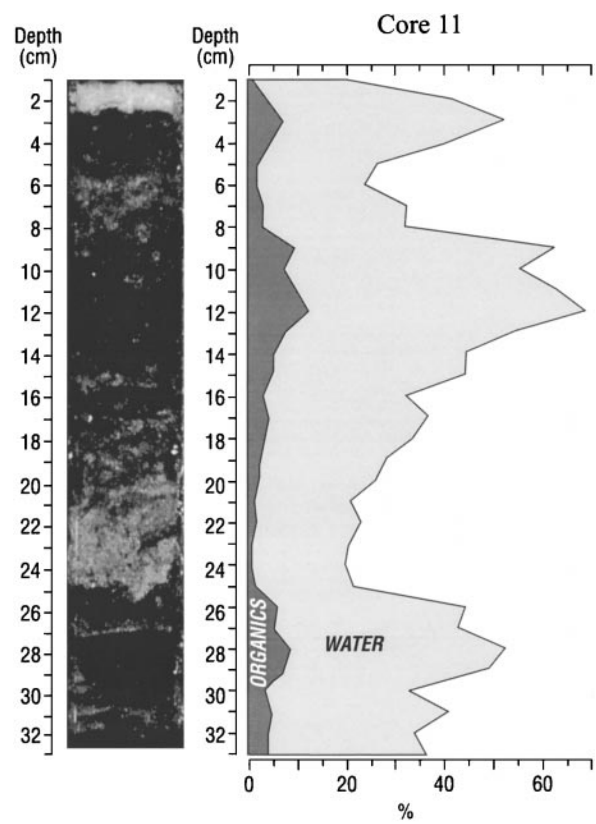

FIG. 4. Photograph of three sand layers at the uppermost 33 cm of core 11 and the corresponding water and organic content curves determined by loss-on-ignition. The prominent sand layer at the top was inferred to be deposited by saltwater intrusion during Hurricane Opal's strike. The other two sand layers are not dated.

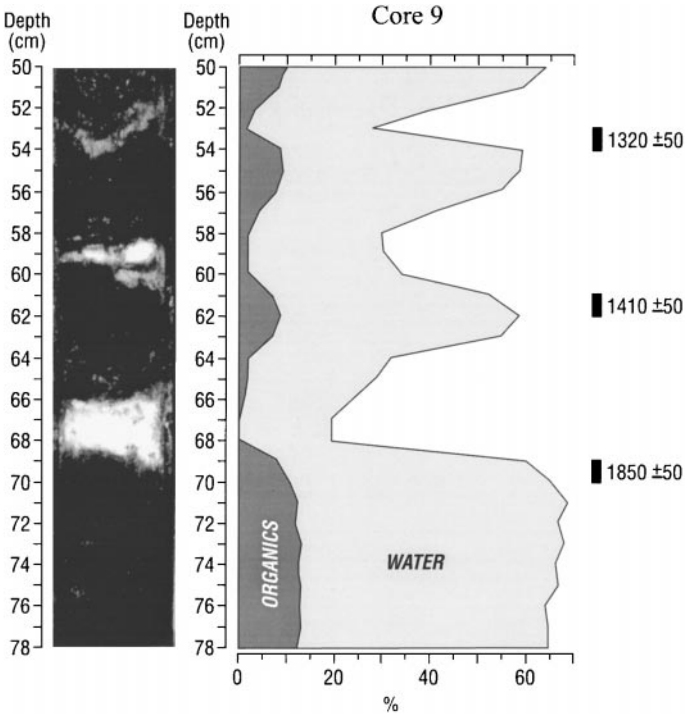

FIG. 5. Photograph of three prominent sand layers in the 50- to 78-cm segment of core 9 and the corresponding water and organic content curves determined by loss-on-ignition. The AMS radiocarbon dates are uncalibrated ^{14}C ages obtained from bulk organic sediments.

more active tidal exchange (e.g., Garden Pond, Horn Island, Mississippi; Terry Cove, Alabama) are typically less organic (<5% organic content) and coarser in texture (Liu and Fearn, unpublished data). The rather uniform organic matter contents of the Western Lake sediments at 10–15% suggest that during the past 5000 yr Western Lake was never a freshwater lake, completely isolated from the Gulf, or significantly more open to the Gulf than it is today. Diatom data confirm these conclusions. Marine and coastal taxa comprise about 75% of the total diatom assemblage throughout the core; brackish taxa average 15%, and freshwater taxa never exceed 5%. Pollen assemblage and concentration data also reveal no significant change in the lake's surrounding vegetation or aquatic environment that might have resulted from a drastic change in the geomorphic or hydrological setting of the Western Lake basin.

MILLENNIAL-SCALE VARIATIONS IN HURRICANE ACTIVITY

The loss-on-ignition curves reveal a dramatic increase in the frequency and thickness of sand layers occurring between 1400 and 3400 ^{14}C yr B.P. (1.6–0.4 m) compared with the previous and subsequent periods (Fig. 6). The eight prominent sand layers and the four less distinct sand layers and lenses, which occur in the upper 1.6 m of the core, are thick (0.5–2.0 cm) and composed of medium to coarse sand. Some layers also contain small shell fragments. Stratigraphic data suggest that 12 catastrophic hurricanes of category 4 or 5 intensity directly struck Western Lake during the past 3400 yr. Remarkably, 11 of these strikes occurred between 1000 and 3400 ^{14}C yr B.P., whereas only one occurred after this interval. Catastrophic hurricane landfalls apparently were much more frequent between 1000 and 3400 ^{14}C yr B.P. than in the past 1000 yr. The relatively few sand layers present between 1.6 and 3.26 m are distinct but thin (<0.2 cm). These data suggest that hurricanes affecting the Western Lake area were less intense and probably less frequent from 3400 to 5000 ^{14}C yr B.P. than in the subsequent period.

An alternative explanation for the quiescent period 3400–5000 ^{14}C yr B.P. is that the dune ridges separating the lake and the Gulf were higher. Consequently, only very high storm surges driven by extremely intense hurricanes could deposit overwash sediments in the lake. No data directly documents the age or geomorphic evolution of the dune ridges in the vicinity of Western Lake (Donoghue and Tanner, 1992; Stapor, 1975). However, we reject this explanation, because the same

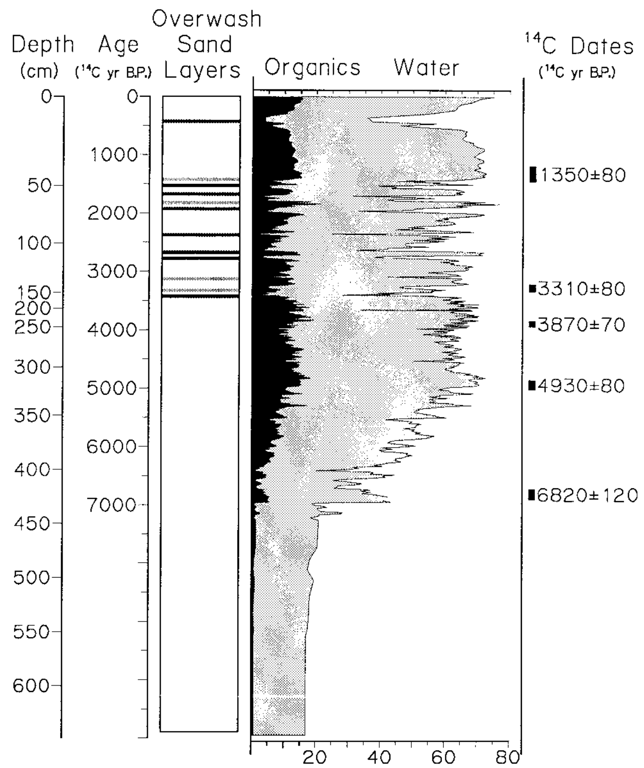

FIG. 6. Loss-on-ignition curves showing water content (% wet weight; gray curve) and organic content (% dry weight; black curve) for core 1 from Western Lake. Sand layers are reflected by abrupt drops in percentage water and organic matter. The stratigraphic column shows prominent sand layers (dark horizontal lines) and less prominent sand layers and lenses (light horizontal lines) occurring in the top 1.6 m. The conventional radiocarbon dates are uncalibrated ^{14}C ages determined from bulk organic sediments. Curves were plotted according to radiocarbon timescale in yr B.P. Corresponding depths (cm) in the core are also shown.

pattern of change occurred simultaneously in Lake Shelby. The record from Lake Shelby, which is surrounded by a different system of beach ridges and dunes from that of Western Lake, indicates that sand layers are absent during the interval 3200–4800 ^{14}C yr B.P., but at least five prominent layers occur in the past 3200 yr (Liu and Fearn, 1993). There is no reason to expect that the local landforms (such as dune heights) of two lakes 150 km apart should change in the same direction synchronously. Instead, the similarity of the two records implies a regional control that involves large-scale processes, such as sea-level oscillation or climatic change.

Another hypothesis is that the increase in sand layers after 3400 yr ^{14}C B.P. was solely caused by a sea-level change. Major discrepancies exist about the chronology and shape of postglacial sea-level curves reconstructed for the northern coast of the Gulf of Mexico (Pirazzoli, 1991). Various researchers have postulated a deceleration of sea-level rise (Wanless and Parkinson, 1989), a leveling of the sea-level curve (Curray, 1965; Nelson and Bray, 1970), and a rapid sea-level rise of 5–6 m (Penland *et al.*, 1987) occurring around 3000–4000 ^{14}C yr B.P. A lower sea level from 3400 to 5000 ^{14}C yr B.P. would have increased the distance of the lake from the barrier beach and the sea, thus making it less likely for overwash deposits to reach the site. However, this scenario is deemed unlikely, because the loss-on-ignition curves from core 1 do not show any drastic change in the sedimentary environment before and after 3400 ^{14}C yr B.P. If the sea level during this period had been lower than the present by 3–5 m, as some sea-level curves suggest (Pirazzoli, 1991), the position of the barrier beach and the dune line would have been at least several hundred meters south of its present position. Such a displacement would have drastically changed the location, size, and morphometry of the lake and would certainly alter the sedimentary environment at the coring site. Even if the location and size of the lake did not change significantly, a lower sea level would decrease the salinity of the lake water. Given sufficiently lowered levels, the basin could have become isolated from the sea and changed into a freshwater lake. No evidence for such limnological change can be found in the sedimentary record. In fact, biogenic silica in the sediment dating to 3400–5000 ^{14}C yr B.P. contains numerous Ebridians (*Hermesinum adriaticum*). This dinoflagellate species inhabits warm water with salinities from 10 to 16 ppt- (Hargraves and Miller, 1974). Its abundance implies slightly higher, not lower, salinities than Western Lake has today.

The most likely explanation of the abrupt stratigraphic change above 1.60 m is that there was a remarkable increase in hurricane frequency and intensity affecting the Florida Panhandle and the Gulf Coast after 3400 ^{14}C yr B.P. as a result of a continental-scale shift in circulation patterns. Based on the chronology of eolian activity and sand dune deposition in the central United States, Forman *et al.* (1995) suggested that during the mid-Holocene thermal maximum (ca. 6000 ^{14}C yr B.P.), the jet stream and the Bermuda High were situated to the north and northeast of their present positions, respectively. As a result of the anticyclonic flow around the southern and western flanks of the Bermuda High, moist air from the south Atlantic was pumped northward along the Atlantic coast of North America. However, by 3000 ^{14}C yr B.P., Neoglacial cooling had caused the jet stream to shift south and the Bermuda High southwest from their ca. 6000 ^{14}C yr B.P. positions, thereby pumping more moisture from the Gulf of Mexico and the Caribbean into the central plains of the United States (Forman *et al.*, 1995). The more southwesterly position of the Bermuda High after 3000 ^{14}C yr B.P. would also result in more hurricanes making landfall on the Gulf of Mexico coast instead of the Atlantic coast (Fig. 7).

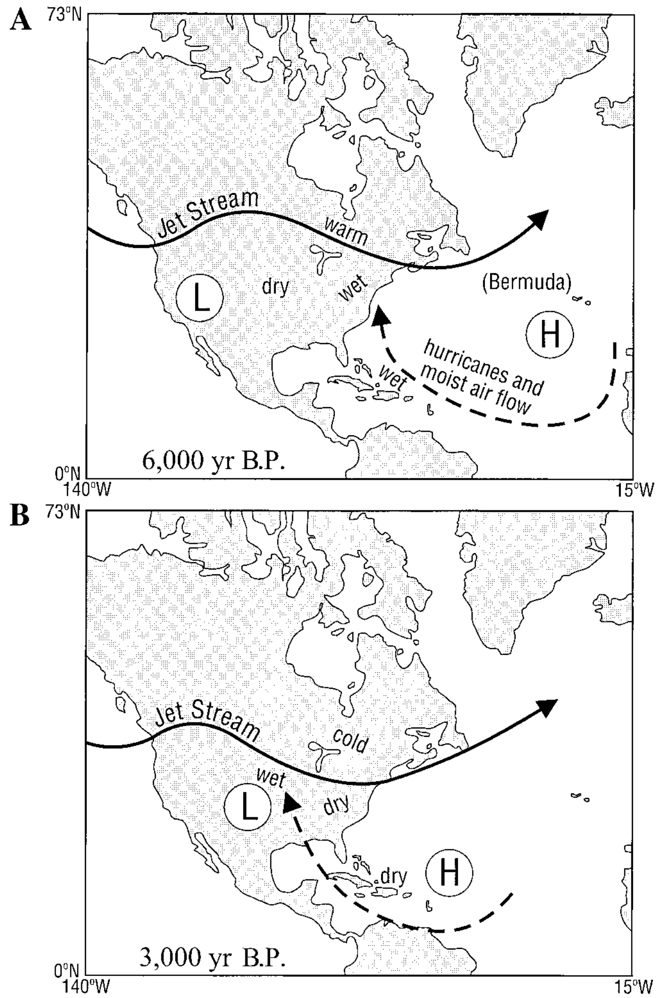

FIG. 7. Inferred mean July position of the jet stream, the Bermuda High, and the thermal low at ca. 6000 ^{14}C yr B.P. (A) and 3000 ^{14}C yr B.P. (B) (modified from Forman *et al.*, 1995) and their paleoclimatic implications.

Paleoclimatic proxy records from many coastal and continental sites in North America and the Caribbean support this postulated shift in atmospheric as well as oceanic circulation around 3000–3500 ^{14}C yr B.P. The strongest evidence comes from Haiti, where an oxygen isotopic record from Lake Miragone indicates an abrupt climatic change toward drier conditions at 3200 ^{14}C yr B.P. (Hodell *et al.*, 1991). A southwestward shift of the Bermuda High would have brought high pressure and subsiding air closer to the eastern Caribbean, resulting in a drier climate in Haiti. In west-central Texas, geological and paleontological data from the Edwards Plateau suggest that the climate was dry from 2500 to 5000 ^{14}C yr B.P., changed to humid from 1000 to 2500 ^{14}C yr B.P., and returned to dry conditions again during the past 1000 yr (Blum *et al.*, 1994; Toomey *et al.*, 1993). A fluvial stratigraphic record from the Lower Pecos River basin in southwestern Texas shows that the hydrological regime shifted from one characterized by infrequent but severe floods to one characterized by frequent, moderate floods ca. 3200 ^{14}C yr B.P. (Patten and Dibble, 1982). Further north, Knox (1993) reported that the frequency and magnitude of overbank floods for the upper Mississippi river tributaries increased abruptly after 3300 ^{14}C yr B.P. In the Great Plains of the central United States, eolian activity decreased significantly as the climate became more humid after 3000–4000 ^{14}C yr B.P. (Forman *et al.*, 1995; Dean *et al.*, 1996). Stratigraphic and geomorphic data from the Finger Lakes and elsewhere from eastern North America suggest a change toward drier conditions at the same time (Dwyer *et al.*, 1996; Leigh and Feeney, 1995). Pollen data from eastern Canada and the northeastern United States also indicate significant cooling after 3000–4000 ^{14}C yr B.P., consistent with a southward shift of the jet stream and the major vegetation zones (Liu, 1990; Webb *et al.*, 1987).

The abrupt decrease in sand layer frequency after ca. 1000 ^{14}C yr B.P. cannot be explained by differences in sea levels, because no significant ($\pm$1 m) sea-level fluctuation has been documented for the Gulf of Mexico during this interval (Pirazzoli, 1991). The sediment-stratigraphic change also predates any minor sea-level fall that may have been attributable to the Little Ice Age (Tanner, 1992; van de Plassche *et al.*, 1998). Remarkably, stratigraphic evidence from Elk Lake, northwestern Minnesota (Dean *et al.*, 1996), and the High Plains (Madole, 1994; Forman *et al.*, 1995) suggests renewed eolian activities and dune reactivation during the past 1000 yr. Abrupt channel trenching and floodplain incision or abandonment in the southern Great Plains also signaled a regional climatic change from moist to dry conditions after 1000 ^{14}C yr B.P. (Hall, 1990; Blum *et al.*, 1994). It is reasonable to infer that the renewed aridity in the midcontinent and reduced catastrophic hurricane landfalls in the Gulf Coast during the past millennium were both due to a northeastward shift of the Bermuda High as part of an atmospheric circulation change.

CONCLUSIONS

No catastrophic hurricane of category 4 or 5 intensity has made landfall in the Western Lake area during the last 130 yr of documentary record, but the sediment stratigraphic data suggest that 12 such hurricanes directly struck Western Lake during the past 3400 yr, yielding a long-term frequency of approximately one hurricane every 280 yr. Therefore, the Florida Panhandle on average has a 0.36% probability of being struck by a catastrophic hurricane of category 4 or 5 intensity in any particular year. This estimate is higher than the 0.16% annual probability (i.e., once every 600 yr) derived from the Lake Shelby record in coastal Alabama (Liu and Fearn, 1993). However, the Lake Shelby record is a minimum estimate, because only the most distinct and prominent sand layers were included in this reconstruction. The Lake Shelby estimate would have been 0.34% (11 strikes in 3200 yr), much closer to that of Western Lake, if all the sand layers had been counted in the probability calculation (Liu and Fearn, 2000).

More importantly, the Western Lake record reveals that significant variability in landfall probabilities occurs at the millennial timescale. During the past 5000 yr, the frequency of catastrophic hurricane landfalls on the northeastern Gulf Coast was low between 3400 and 5000 ^{14}C yr B.P. and since 1000 ^{14}C yr B.P., but increased dramatically between 1000 and 3400 ^{14}C yr B.P. During the "hyperactive" period of 1000–3400 ^{14}C yr B.P., especially in the first millennium A.D. (ca. 1000–2000 ^{14}C yr B.P.), catastrophic hurricanes directly struck the Western Lake area about five times per 1000 yr, hence with a landfall probability of ca. 0.5% per yr. By contrast, the annual landfall probability for the recent, more quiescent, millennium is only about 0.1%.

The intermillennial variability in catastrophic hurricane landfalls documented in this study has significant paleoclimatic as well as practical implications. Current estimates of landfall probabilities, including the traditional actuarial approach of risk assessment used by insurance companies and policy markers, are based on the instrumental record that spans no more than 130 yr and contains few catastrophic hurricane strikes (Michaels *et al.*, 1997; Pielke and Pielke, 1997). The Western Lake data demonstrate that, like other paleoclimatic proxy records that reveal "warm climate surprises" (Overpeck, 1996), paleohurricane records from the past century or even the past millennium are not long enough to capture the full range of variability of catastrophic hurricane activities inherent in the Holocene climatic regime. If future climatic changes, whether or not related to the anticipated greenhouse warming, lead to a return of a "hyperactive" hurricane regime characteristic of the first millennium A.D., then the northeastern Gulf Coast is expected to experience a dramatic increase in the frequency of strikes by catastrophic hurricanes.

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