Lake-sediment record of late Holocene hurricane activities from coastal Alabama

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ABSTRACT

Coastal lake sediments contain a stratigraphically and chronologically distinct record of major hurricane strikes during late Holocene time. Frederic—a category 3 hurricane that struck the Alabama coast on the Gulf of Mexico in 1979—left a distinct sand layer in the nearshore sediments of Lake Shelby as a result of storm-tide overwash of beaches and dunes. Sediment cores taken from the center of Lake Shelby contain multiple sand layers, suggesting that major hurricanes of category 4 or 5 intensity directly struck the Alabama coast at ca. 3.2–3.0, 2.6, 2.2, 1.4, and 0.8 ka (^{14}C yr), with an average recurrence interval of ~600 yr. The Alabama coast is likely to be struck by a category 4 or 5 hurricane within the next century.

INTRODUCTION

Hurricanes are an important factor in the climate and coastal evolution of the Gulf Coast region of the United States (Conner et al., 1989; Simpson and Riehl, 1981). Since A.D. 1899, 62 hurricanes have directly affected the ~1200-km-long coastline between Apalachicola, Florida, and Matagorda Bay, Texas (Neumann et al., 1987). Of these, 36 were "minor" hurricanes of category 1 (maximum sustained wind speed of 119–153 km/h) or 2 (154–177 km/h) intensity, according to the Saffir-Simpson hurricane intensity scale. Of the remaining "major" hurricanes, 18 were category 3 (179–209 km/h), seven were category 4 (211–249 km/h), and only one (Camille in 1969) was category 5 (>249 km/h). Thus, for any particular place along this coast, the probability of a direct strike by a category 4 or 5 hurricane is quite low. Unfortunately, the documentary record is too short for estimating the recurrence interval of these rare but most destructive hurricanes. Documentary records of hurricanes affecting the eastern United States date back only to A.D. 1871; with far less confidence, they can be stretched back to the 1700s from written accounts by early settlers (Neumann et al., 1987; Ludlam, 1963). Therefore, geologic data offer the only hope of reconstructing a prehistoric record of intense hurricanes and deciphering any long-term changes in hurricane activities.

Storms can leave distinctive sedimentary structures in ancient shallow-marine deposits (e.g., Aigner, 1985; Duke, 1985). Recently, Davis et al. (1989) inferred that hurricanes produced graded or homogeneous facies of sand, shell gravel, and mud found in predominantly clastic sediments of late Holocene age in coastal lagoonal bays of Florida. We demonstrate here that a stratigraphically and chronologically distinct record of major hurricane strikes during late Holocene time can be obtained from coastal lake sediments.

STUDY SITE

Our record comes from Lake Shelby, one of three freshwater lakes within Gulf State Park along the Alabama coast on the Gulf of Mexico (Fig. 1). All three lakes are situated on the Holocene beach-ridge plain south of the Pamlico barrier, a relict shoreline of probable Sangamon age (Smith, 1986; Otvos, 1985). Lake Shelby is separated from the Gulf of Mexico by a sandy beach only 250 m wide and is surrounded by complex systems of pine-dominated beach ridges with sand dunes ~2–4 m high. The lake is ~2.8 km long, has a flat bottom 3–4 m deep, and occupies a small drainage basin with no significant inflowing streams. Sediment sources for Lake Shelby are limited; the lake was isolated from adjacent Middle Lake until a canal was dug to connect them, in the 1960s. Modern sediment accumulating at the bottom of this humic-water lake is gyttja with 35%–40% (dry weight) organic matter and little or no sand.

STRATIGRAPHIC RECORD OF HURRICANE FREDERIC

Since A.D. 1899, nine hurricanes have made landfall on the Alabama coast. Four of these (in 1906, 1916, 1926, 1979) were category 3 hurricanes; the intensity of the rest was only category 1 or 2 (Neumann et al., 1987). The last, and the most destructive, category 3 hurricane directly striking the Alabama coast was Frederic in September 1979. Hurricane Frederic's eye made landfall on Dauphin Island, Alabama, about 50 km west of Lake Shelby. Frederic brought wind gusts of up to 233 km/h (145 mi/h) and 22–28 cm of rain in a 24-h period to coastal Alabama and adjacent Mississippi. The 4.8-m-high storm surge completely overwashed the barrier beach and inundated the low-lying beach-ridge plain around Lake Shelby for several days. The surge eroded the gulf shoreline backward by 24–30 m and leveled the dune fields by 1.5–2.5 m (U.S. Army Corps

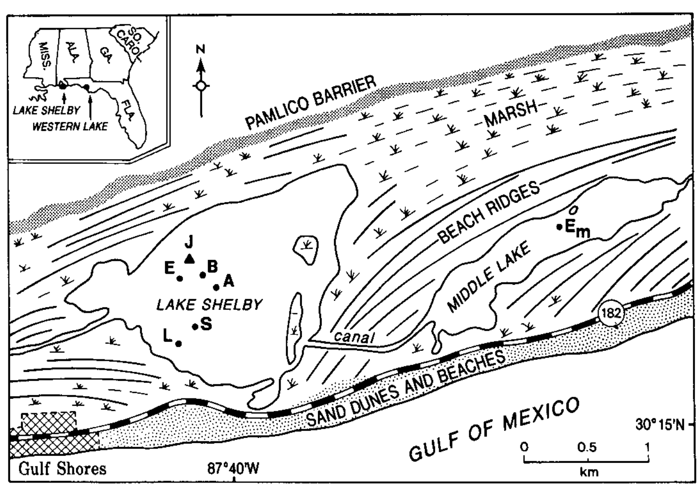

Figure 1. Geomorphic setting of Lake Shelby, Middle Lake, and Western Lake (see inset), showing location of sediment cores used in stratigraphic study (solid circles) and in ^{137}Cs study (triangle). Black and white line is Alabama State Highway 182.

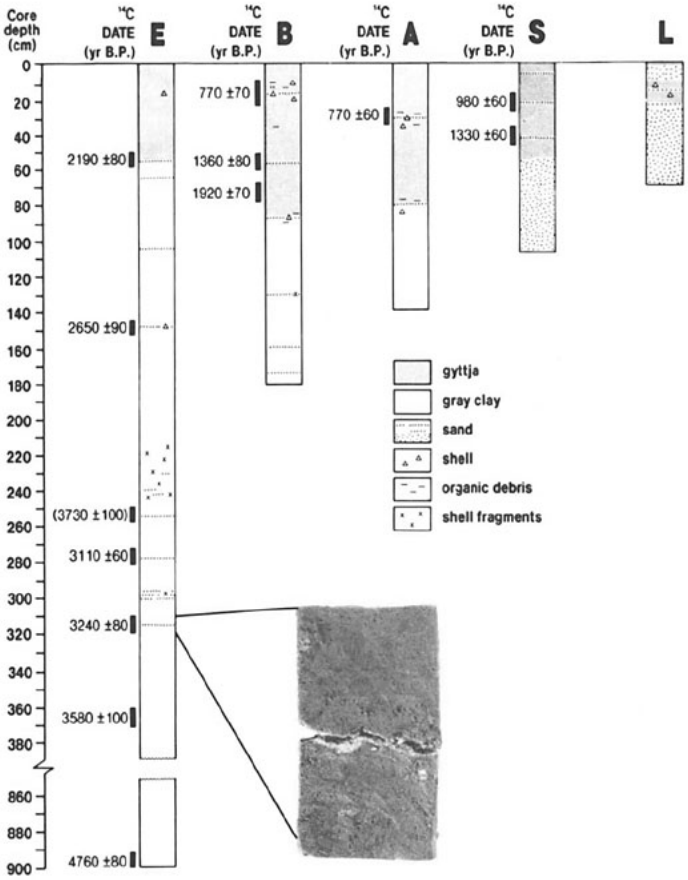

Figure 2. Radiocarbon-dated stratigraphic units of Lake Shelby cores A, B, E, L, and S. All ages shown here and in text are uncalibrated ^{14}C ages unless specified otherwise. Date of 3730 ± 100 yr B.P. (Beta-38387) in core E is rejected for being too old, perhaps because of contamination by dead C in shell fragments. Inset photograph shows sand layer in core E, at 314 cm, sandwiched between lagoonal clay. Lines on core surface are scratch marks produced by spatula.

of Engineers, 1981). A section of the road (State Highway 182) between the lakes and the Gulf of Mexico was washed away, creating a tidal inlet into Middle Lake.

On the basis of these geomorphic impacts of Hurricane Frederic, we hypothesize that a major hurricane would cause sand to enter Lake Shelby by means of tidal overwash and dune erosion and that this sand would form a layer on the lake bottom. If Lake Shelby's geomorphic setting has not changed drastically during the late Holocene, then the thickness and horizontal extent of such sand layers should roughly reflect the intensity of the hurricanes striking the Alabama coast. Thus, a proxy history of hurricane strikes could be reconstructed on the basis of the stratigraphy and chronology of sand layers in the sediments of Lake Shelby.

We took multiple cores at different parts of Lake Shelby to search for the stratigraphic records of Hurricane Frederic. Despite its catastrophic geomorphic impacts, Frederic left only a spatially limited sedimentological record in the nearshore sediments of Lake Shelby. Cores (A, B, E—see Fig. 1) taken from the central part of the lake do not contain sand layers at the top attributable to Frederic's impacts. We found the stratigraphic marker attributable to Frederic's impact in two short cores (L and S) taken in 2.1–2.9 m of water close to the south shore where the tidal overwash occurred (Fig. 1). These cores were retrieved with a Rowley-Dahl sampler made up of a 2.0-m-long clear-plastic tube fitted with a piston. Care was taken to hold the core upright in the sampling tube to ensure that the soft, uppermost organic sediment was not disturbed before photographing and subsampling in the field. In core L, the storm deposit takes the form of a 9-cm-thick layer of white sand underlying 1 cm of gyttja at the core top (Fig. 2). We are not aware of any mechanism other than the Frederic-induced tidal overwash and dune erosion that could possibly have deposited a sand layer in a part of the lake bottom where gyttja normally accumulates. The uppermost thin layer of gyttja is consistent with the post-Frederic organic deposition accumulating since 1979. Below the white sand layer is a section of gyttja containing two distinct sand layers ~0.2–0.3 cm thick, each of which may represent an earlier hurricane. In core S, located about 325 m offshore, the Frederic sand layer thins to <0.1 cm and becomes indistinct. This sand layer is inferred to thin out completely within 400 m from the south shore.

RECONSTRUCTING PREHISTORIC HURRICANE ACTIVITIES

The stratigraphic signature of Frederic in cores L and S can be used as a modern analogue for interpreting the stratigraphies of cores taken from the central part of the lake. Cores A, B, and E (see Fig. 1) were taken at sites where water depths are 3.0–3.5 m. Two short cores (A and B) were collected with a clear-plastic Rowley-Dahl sampler; E is a 9-m-long core taken with a modified Livingstone sampler. All three cores contain 55–85 cm of gyttja overlying gray lagoonal clay (Fig. 2). The gyttja-clay boundary was dated by ^{14}C at 2.190 ka (sample Beta-39536), and the lowermost clay sample from core E yielded a date of 4.760 ka (±80 ^{14}C yr) (Beta-38187). The gray clay unit contains about 95%–98% clay, <5% fine sand, and little or no silt, comprises 10% organic matter, and lacks discernible sedimentary structures throughout. It is dominated by diatoms characteristic of brackish and marine environments, and it resembles sedimentologically modern sediment samples collected from Terry Cove, a sheltered, quiet-water lagoon east of Lake Shelby. The stratigraphy suggests that a low-energy lagoonal environment persisted in the Shelby basin from 4.8 ka (^{14}C yr) until the freshwater lake was formed at about 2.2 ka.

As our model predicts, the cores contain multiple sand layers attributable to past hurricane impacts in both the gyttja and lagoonal clay sections. These sand layers are typically 0.1–1 cm thick; are composed of rounded, white, coarse sand grains that resemble beach sand; and commonly have sharp contacts with the clayey sediments above and below (Fig. 2). In core E, the more prominent and individually distinct sand layers are at 55 cm (the gyttja-clay transition) and at 65, 104, 158, 240, 256, 278, 290–293 (several layers), and 314 cm. The section below 314 cm (abbreviated in Fig. 2) contains homogeneous gray clay without any sand layers or sedimentary structures. Both cores A and B contain a distinct sand layer associated with bivalve shells (*Rangia* sp.) and coarse organic detritus at 30 cm and 15 cm, respectively. Core B also contains another distinct sand layer at 55 cm and several less distinct ones in the lagoonal clay section. The two upper sand layers in core B probably correlate with the two at 20 and 42 cm (each about 0.2 cm thick) in the nearshore core S.

These sand layers probably represent direct strikes by major hurricanes of category 4 or 5 intensity, because Frederic—a high category 3 hurricane causing catastrophic dune erosion and tidal overwash—did not leave an identifiable sand layer at our coring sites in the middle of the lake. Therefore, those prehistoric hurricanes that did leave a sedimentological record in the center of Lake Shelby must have been much stronger, and their geomorphic impacts must have been more severe. Moreover, these hurricanes probably made landfall within 50 km (the typical radius of destructive winds in the wind field around the eye of a catastrophic hurricane) of the Alabama coast to have caused the catastrophic geomorphic impacts required to deposit these sand layers in the middle of Lake Shelby. In 1969, Camille, a category 5 hurricane, made landfall near the Mississippi-Louisiana border about 160 km west of Lake Shelby; Camille caused catastrophic destruction to areas along its path but had only a minor impact on the Alabama coast. Thus, the record from any individual site reflects only direct hits by severe hurricanes.

Tsunamis can also produce sand layers in coastal organic deposits of late Holocene age. Such tsunami deposits have been found in Washington, Oregon, and Japan (Atwater, 1987; Atwater and Moore, 1992; Darienzo and Peterson, 1990; Minoura and Nakaya, 1991). In addition, silt layers found in lake-sediment cores from the hilly regions of Quebec have been attributed to landslides and intensified slopewash triggered by earthquakes (Doig, 1990). These alternative interpretations are highly unlikely for coastal Alabama because the northern Gulf of Mexico coast is a tectonically and seismically stable region where earthquakes are rare. Moreover, intense winter storms or extratropical cyclones may cause significant erosion and sand transport along the Atlantic coast of North America, but they are less common along the Gulf of Mexico coast where their associated storm surge heights and maximum wind speeds are typically less than those of category 4 or 5 hurricanes. Such high energy is required to deposit sand layers such as those in the center of Lake Shelby (Dolan et al., 1988; Boyd and Penland, 1981).

Using the radiocarbon method, we dated the bulk organic sediments encompassing the more prominent and individually distinct sand layers to establish a chronology of major hurricane strikes (Fig. 2). The less prominent sand layers and diffuse sand lenses in these cores were not dated. Average sedimentation rates calculated by interpolating between these dates range from ~0.03 cm/yr in the gyttja section to 0.22–0.45 cm/yr in the lagoonal clay section below.

We documented the down-core extent of hurricane-induced sediment mixing by examining the cesium-137 (^{137}Cs) profile of a short core of soft, organic sediment taken from the center of the lake (Fig. 1). ^{137}Cs, a radioactive fallout nuclide derived from atmospheric nuclear tests, was absent in natural environments before 1954 (Pennington et al., 1973); ^{137}Cs was present from the top of the core down to 20 cm depth where the sediment is independently estimated to be about 500 yr old on the basis of the radiocarbon chronology. This is only slightly deeper than the typical depths of bioturbation (3–15 cm) recorded in small, deep, holomictic lakes in temperate regions unaffected by hurricanes (Davis, 1974). We conclude that bioturbation and hurricane-induced disturbance result in limited reworking of soft, organic lake sediments but not the obliteration of the storm-generated sand layers in the sedimentary record.

The combined radiocarbon stratigraphy of these sand layers suggests that catastrophic hurricanes of category 4 or 5 intensity directly struck the Lake Shelby area at ca. 3.2–3.0, 2.6, 2.2, 1.4, and 0.8 ka (^{14}C yr) (or 3.5–3.3, 2.8, 2.2, 1.3, 0.7 ka calendar yr), implying a recurrence interval of ~600 yr. No hurricane of category 4 or 5 intensity has made landfall in coastal Alabama during the past 120 yr of documentary record. Our reconstructed frequency of once every 600 yr for these direct hits by intense hurricanes is probably a conservative or minimum estimate, because the stratigraphic record of hurricanes preserved in one core may be incomplete and we have not dated the less distinct or less prominent sand layers that may represent less intense hurricanes or less direct strikes. Since our data suggest that the last intense hurricane struck this area directly ~770 ^{14}C yr ago, it is quite probable that the Alabama coast will be struck by a category 4 or 5 hurricane within the next century.

ABRUPT ENVIRONMENTAL CHANGE AT 3.2 KA

An intriguing problem in the 9 m core is that the sand layers are confined to the upper 3.2 m (Fig. 2). The complete absence of sand layers in sediments older than ca. 3.2 ka (^{14}C yr) may imply a more tranquil climatic regime prior to that time, in which there were fewer or weaker hurricanes affecting the Alabama coast. This lack of older sand may signal a climatic change of regional significance across the Caribbean Basin and the Gulf of Mexico. An abrupt shift in oxygen isotope values recorded in a high-resolution stratigraphic record from Lake Miragoane, Haiti, indicates a sudden onset of a drier climate at 3.2 ka (Hodell et al., 1991). Paleohydrologic and archaeological records from the Pecos River basin in southwest Texas suggest frequent and severe floods during the period 4.5–3.2 ka, concomitant with a warm and dry climate, switching to a more mesic climate with fewer and smaller floods during the period 3.2–2.0 ka (Patten and Dibble, 1982). One possible mechanism suggested for the extreme floods in the lower Pecos River is the unusual incursion of hurricanes into southwest Texas from the Gulf of Mexico, as demonstrated by Hurricane Alice that in 1954 penetrated far inland along the Rio Grande and caused very intense rainfall and the largest historical flood in Texas (Bryant and Holloway, 1985). A regional shift in circulation patterns at 3.2 ka may have brought drier climate to Haiti and steered the hurricanes into more eastward tracks, away from Texas and toward Alabama and Florida.

Alternatively, the geomorphic setting of the Shelby basin may have been different before 3.2 ka so that the depositional environments were not conducive to the preservation of hurricane records in the sediments prior to that time. Notably, the section between 2.16 and 3.14 m contains several distinct sand layers as well as sand lenses mixed with tiny shell fragments. A sea level rise at ca. 3.2 ka could have initiated the formation of the beach-ridge plain along the Alabama coast and thus brought a source of sand to the proximity of the coring sites. No data exist on the age or origin of the Holocene beach-ridge plain or the modern barrier beach in coastal Alabama (Smith, 1986; Otvos, 1985; Stapor, 1975); thus we cannot evaluate this hypothesis. The only late Holocene sea-level curve constructed for this part of the Gulf of Mexico coast, albeit of coarse resolution and supported by few radiocarbon dates, suggests a sea-level lowstand during the period 4.0–2.7 ka and a rise at 2.7 ka (Tanner et al., 1989), apparently out of phase with the 3.240 and 3.110 ka dates (Beta-38389 and Beta-38388, respectively) for the lowest sand layers.

Regardless of the cause, the data from Lake Shelby seem to suggest an episode of abrupt environmental change in coastal Alabama at ca. 3.2 ka. This interpretation is strengthened by new data from cores collected from two other coastal lakes situated in similar geomorphic settings. A 9.34 m core (core E_m) from Middle Lake, which is adjacent to Lake Shelby but enclosed by different beach-ridge systems (Fig. 1), shows a similar stratigraphy with an abrupt increase in sand layers upward from 3.0 m, suggesting that the stratigraphic changes found in Lake Shelby are not due to local, unique geomorphic controls. More significant is that a 6.45 m core from Western Lake at Grayton Beach, Florida (Fig. 1), about 150 km east of Lake Shelby, shows a similar stratigraphic change at 1.59 m, dated at 3.310 ka (±80 ^{14}C yr) (Beta-60240), suggesting a distinct increase in the frequency and magnitude of perturbations. Our data from multiple sites thus suggest that this abrupt environmental change at ca. 3.2 ka was controlled by large-scale processes such as regional climatic shift or sea-level change.

SUMMARY AND CONCLUSIONS

Intense hurricanes (categories 4 and 5) are historically rare events. Yet because of their highly destructive forces, they play an important role as geomorphic agents in causing coastal landform changes, as ecological agents in ecosystem disturbance and succession, and as natural hazards in causing catastrophic destruction to life and property (e.g., Conner et al., 1989; Walker et al., 1991; Simpson and Riehl, 1981). It has been pointed out that intense hurricane activity in the western Atlantic and Gulf of Mexico region is part of global teleconnections and may be linked to sub-Saharan droughts and El Niño–Southern Oscillation events (Gray, 1984, 1990; Caviedes, 1991). The frequency and predominant tracks of intense hurricanes are thus expected to have varied historically as a function of global climatic changes occurring at various time scales (Barron, 1989; Wendland, 1977; Hobgood and Cerveny, 1988). Therefore, reconstructing the late Holocene history of these hurricanes and understanding their long-term frequency and recurrence potential is of great theoretical and practical value. The importance of this task is underscored by recent predictions of increased frequencies of intense hurricanes in the western Atlantic correlative with the termination of the 20-yr drought cycle in sub-Saharan Africa since 1989 (Gray, 1990). Moreover, climate modeling results based on scenarios of greenhouse warming predict a 40%–50% increase in hurricane intensities in response to warmer tropical oceans (Emanuel, 1987). These model predictions must be calibrated and tested with long-term climate data that contain a proxy record of hurricane activities during various climatic episodes in the past. Lakes along the northern Gulf of Mexico coast have the potential of yielding multiple proxy records that can be integrated regionally to document the chronological and spatial variations in hurricane activities for the past several millennia.

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