Available online at www.sciencedirect.com
ScienceDirect
Quaternary International 195 (2009) 53–68

5000 year sedimentary record of hurricane strikes on the central coast of Belize

T.A. McCloskey*, G. Keller

Department of Geosciences, Princeton University, Princeton, NJ 08544, USA

Available online 14 March 2008

Abstract

The central coast of Belize has been subject to hurricane strikes throughout recorded history with immense human and material cost to the Belizean people. What remains unknown is the long-term frequency of hurricane strikes and the effects such storms may have had on the ancient Maya civilization. Our sedimentary study of major hurricane strikes over the past 5000 years provides preliminary insights. We calculate that over the past 500 years major hurricanes have struck the Belize coast on average once every decade. One giant hurricane with probably particularly catastrophic consequences struck Belize sometime before AD 1500. A temporal clustering of hurricanes suggests two periods of hyperactivity between ~4500 and 2500 ^{14}C yr BP, which supports a regional model of latitudinal migration of hurricane strike zones. Our preliminary hurricane data, including the extreme apparent size of the giant event, suggest that prehistoric hurricanes were capable of having exerted significant environmental stress in Maya antiquity.

1. Introduction

Hurricanes are capable of exerting tremendous societal stress. In the North Atlantic Basin, which includes the Gulf of Mexico and Caribbean Sea, hurricanes have killed 300,000–500,000 people over the past 500 years (Rappaport and Fernandez-Partagas, 1997). Average annual costs in the United States alone are in the billions of dollars (Pielke and Pielke, 1997). The extreme devastation inflicted on the United States during the 2004 and 2005 seasons demonstrates that hurricane-generated damages can be economically important on a national scale. The same is true for the coast of Belize, which has been subject to devastating hurricane strikes through recorded history. This includes six major hurricanes of category 3 or higher at landfall within the last 70 years. These are the unnamed hurricane of 1931, hurricanes Janet (1955) and Keith (2000), which passed to the north of Belize City, Hattie (1961) and Greta (1978), which made landfall at Mullins River and just north of Dangriga, respectively, and Iris (2001) (Fig. 1). All of these hurricanes devastated coastal towns, except for Iris (2001), which made landfall in a relatively unpopulated area near Monkey River and devastated the tropical forest. The immense human and material costs to the Belizean people are well documented.

Hurricanes were already mentioned in Maya hieroglyphics (Rappaport and Fernandez-Partagas, 1997). But it was not until 1495, when a hurricane destroyed the town of Isabella founded by Columbus on the island of Hispañola, that the earliest dated Caribbean hurricane was recorded (Rappaport and Fernandez-Partagas, 1997). However, despite ongoing improvements and corrections the early historical records are still far from complete, with early storms mainly recorded from populated areas and when encountered at sea, with many records subsequently lost (Mock, 2004; Chenoweth, 2006, 2007; Garcia-Herrera et al., 2007). A fairly comprehensive list of landfalling hurricanes has been compiled since 1871 (Neumann et al., 1999), but complete and reliable records for the North Atlantic began only with aircraft reconnaissance in the 1940s.

A much longer storm record can be obtained from the sedimentary record, specifically from hurricane-deposited sand layers in coastal lakes, marshes and swamps. The underlying assumption is that major or "intense" hurricanes (category 3 or greater) generate large storm surges,

*Corresponding author. Present address: Department of Oceanography and Coastal Sciences, Louisiana State University. Baton Rouge, LA 70803, USA. Tel.: +1 225 578 0470; fax: +1 225 578 6423.
E-mail address: tmcclo1@lsu.edu (T.A. McCloskey).

1040-6182/$ - see front matter
doi:10.1016/j.quaint.2008.03.003

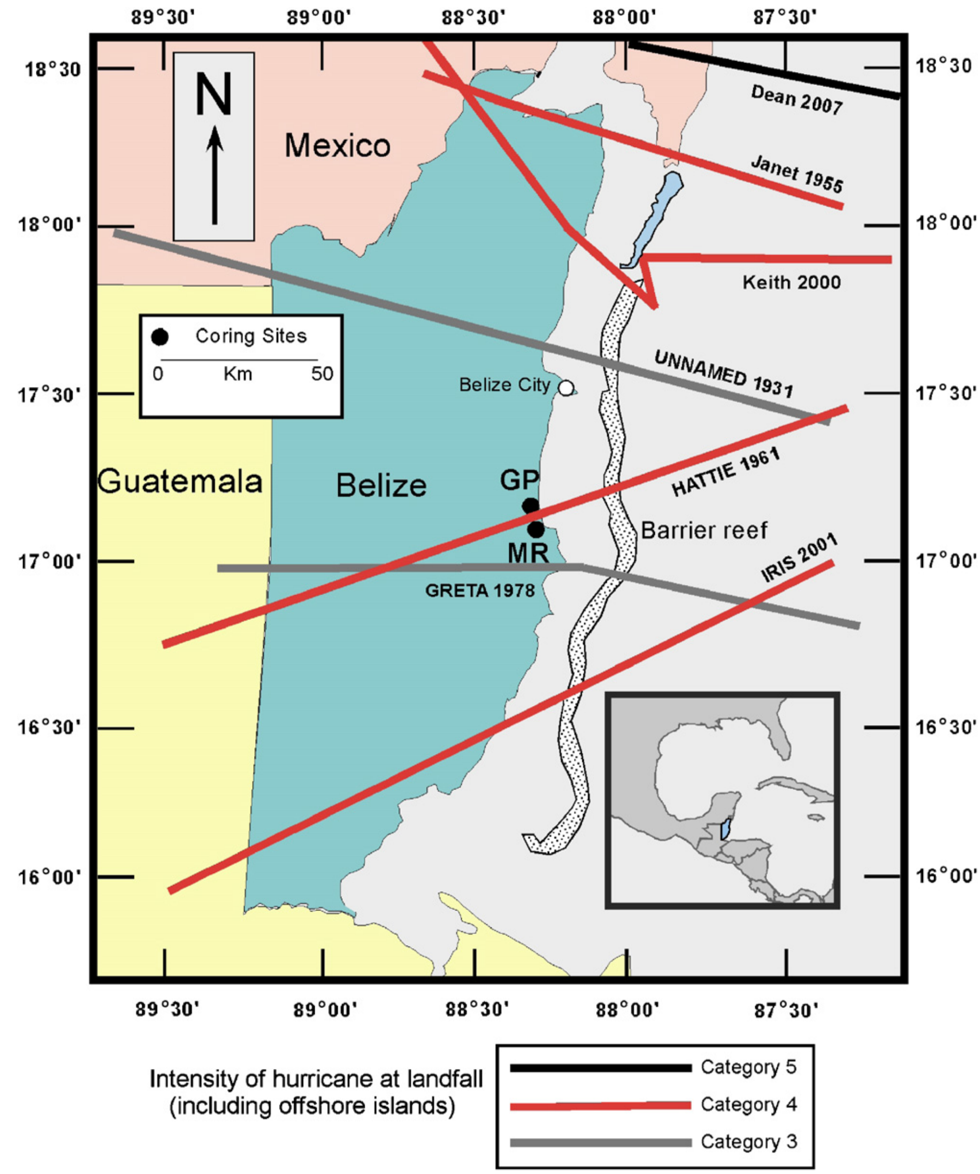

Fig. 1. Map of Belize showing coring sites and tracks of major hurricanes (category 3 or higher at landfall) since 1931.

which crest barrier dunes and deposit sand fans landward. These sand layers become interbedded with the normally deposited coastal vegetation, which permits the establishment of multi-millennial hurricane strike records. The long-term hurricane record has been investigated in recent years by historical and geological methods as a discipline labeled paleotempestology. To date such studies have been conducted largely along the Gulf and Atlantic Coasts of the United States in an effort to understand cycles of hurricane activity and establish risk parameters for susceptible areas (Liu and Fearn, 1993, 2000; Collins et al., 1999; Donnelly et al., 2001a, b, 2004; Scott et al., 2003). In contrast, only three published studies exist to date from the more often struck Caribbean (Bertran et al., 2004; Donnelly, 2005; Donnelly and Woodruff, 2007).

The main objective of this study is to extend the paleotempestology record to the relatively unstudied Western Caribbean region of Belize by determining the frequency of hurricane strikes over the past 5000 years. This record can then be used to evaluate the relationship between strike frequencies in the Caribbean and other parts of the North Atlantic Basin, and to estimate the level of hurricane-generated stress upon the ancient Maya civilization.

2. Regional setting

2.1. Geological

Both the historical frequency of hurricane strikes and the relatively stable coastal geomorphology promote the coast of Belize as a paleotempestology study site. With the offshore barrier reef acting as a buffer, the low-energy wave regime inside the reef system results in highly reflective beaches, which are geomorphologically the most stable, with relatively low levels of dune destruction (Short and Hesp, 1982; Wright and Short, 1984), thereby reducing the temporal variability of site sensitivity.

The northern half of Belize is part of the low lying carbonate Yucatan platform, while the south is dominated by the Maya Mountains, a faulted block composed of Paleozoic basement rocks and granitic intrusions, capped by Cretaceous limestone (Donnelly et al., 1990). The division between these two morphotectonic provinces occurs at the latitude of Belize City. The study sites are located slightly to the south of this division on a coastal plain formed of terrigenous Quaternary sediments, in an area of minimal topographic relief characterized by marshes, swamps and scrubby wetlands. Drainage is minimal and low laying areas are waterlogged throughout the year; soils are typically peats and marls. The first significant topographical relief is >6 km west of the Mullins River site and ~4 km west of the Gales Point site (Fig. 2). The Barrier reef lies ~20 km offshore, separated from the coast by a shallow shelf lagoon, which is characterized by sediments rich in quartz sand, mollusc and *Halimeda* marl, carbonate *Halimeda* sand and *Thalassia* beds (James and Ginsburg, 1979).

The Mullins River (MR) and Gales Point (GP) localities are within sight of each other along a nearly north–south running beach, which trends east near Mullins River (Fig. 2).

2.2.1. Gales Point

The area surrounding Gales Point is particularly flat and low. An elevated road winds through >2 km of swamps

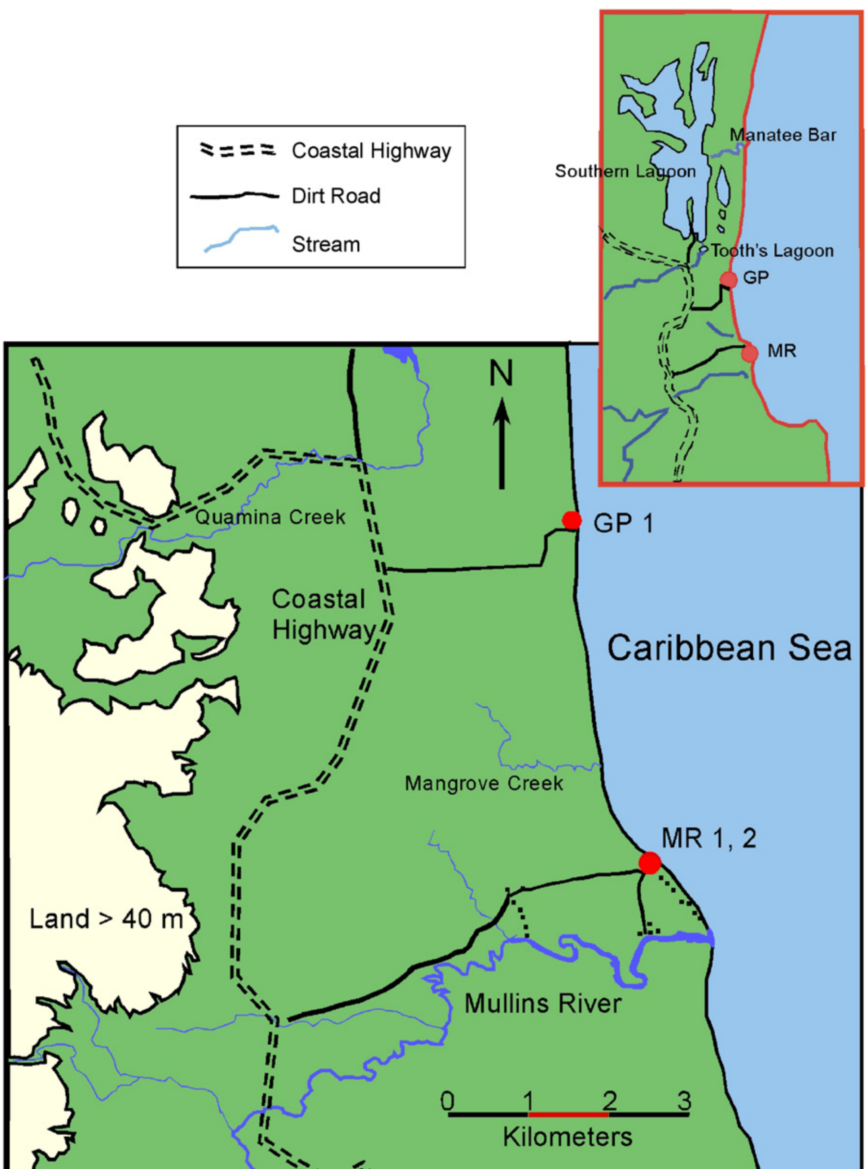

Fig. 2. Site map, showing coring sites (dots, red dots online), buildings (squares), watercourses (solid gray lines, solid blue lines online), Coastal Highway (dashed double lines), dirt roads (solid black lines) and land over 40 m (hatched area, white area online).

and marshes with no clearly defined waterways. The nearest mapped waterway is Quamina Creek, located ~2 km from Gales Point. Quamina Creek is a small sluggish stream that emerges from the hills 4 km to the west, and drains north into the sea via Tooth's Lagoon, Southern Lagoon, and the Manatee Bar. All other drainage appears to be by sheet flow. The transect for this study is normal to the shore, with cores obtained at 10 m intervals from 60 to 110 m from the shoreline. The elevation of the profile rises progressively inland and away from the sea, reaching a maximum of ~1.5 m on the crest of the foredune at a distance of 35 m. All surface and underlying sediments up to the foredune appear to be sand. Beyond 35 m, the elevation decreases, soil appears at about 50 m from the shoreline and the vegetation becomes progressively thicker. Beyond 95 m swamp predominates at roughly sea level, with standing water and distinct swamp vegetation, characterized by palms and hardwoods.

2.2.2. Mullins River

The Mullins River site (MR) is on slightly higher land approximately 4.5 km to the south and 1 km north of the mouth of Mullins River, in an area of swamp, marsh and forest. The transects' seaward edges begin in a small marsh that progressively changes inland first to tropical forest and then to thick palmetto swamp (Fig. 3). Except for the marsh, which is in a shallow depression, the surface topography is generally flat at an elevation of less than 1 m up to the palmetto marsh at ~75 m. At that point, the land dips abruptly to near sea level. A small dirt track runs along the shore to the nearly abandoned seaside village of Mullins River, which was destroyed during Hurricane Hattie (1961). A new village was established farther inland.

3. Methods

For this investigation a total of 21 cores were obtained in two parallel transects at Mullins River, which marks the point of eyewall impact for Hurricane Hattie (1961). A single transect was taken at Gales Point, 4.5 km to the north. Coring was principally by Vibracorer and Russian Peat Borer, with a few initial cores obtained by means of 4.2 cm diameter galvanized steel pipes that were manually driven into the ground. Cores were obtained in parallel transects perpendicular to the coast and spaced at about 10 m, except where obstructed by vegetation. At Gales Point, cores were taken from 60 to 110 m inland. At Mullins River, two transects were cored 75 m apart starting at 15 and 20 m from the shoreline and extending to 85 and 120 m inland. Core length is variable with most cores between 0.8 and 1.5 m, though two cores reach 3 m. Significant sediment compaction occurred only in the manually driven steel pipes, which were adjusted for compaction or omitted from this study.

In the laboratory, the cores were split lengthwise and the sediments visually and optically examined for grain size, color, texture, composition and lithological changes at 1 cm intervals. The sediments were classified according to the percentage of coarse, medium, and fine sand, silt, clay and organic matter. Samples from each sand or sandy clay layer were washed through a 63-μm sieve and the dried residues examined under the microscope for marine microfossils

Fig. 3. Photo of site of Mullins River Line 2, looking from the Caribbean Sea inland, showing the transition from marsh to tropical hardwood forest. The grass in the marsh is approximately waist high. The palmetto swamp farther inland is not visible.

(e.g., foraminifera, diatoms, sponge spicules, ostracodes, bivalve and gastropod shells) as evidence of hurricane transport. Lithologs were based on these data for each core.

Loss-on-ignition was analyzed for each core at 4–5 cm intervals, with closer spacing across lithological changes, in order to measure the organic content. Samples were dried overnight at 50 °C, then weighed, heated in a convection oven at 600 °C for 3 h, then reweighed to determine the amount of organic carbon ignited (Dean, 1974).

Radiocarbon age control was obtained from five samples (peat layers or larger organic fragments) closest to selected sand layers identified as hurricane deposits and the analyses performed at Woods Hole Oceanographic Institution (Table 1). Calibration of ^{14}C yr BP to cal BP were performed on the CALIB5.0.2 program from the Queens University Belfast's website (http://calib.qub.ac.uk/calib/) based on Stuiver and Reimer (1993). References for calibration datasets are from Reimer et al. (2004).

4. Results

4.1. Hurricane events

Interbedded sand/clay layers were identified as hurricane generated on the basis of lithologic, sedimentologic, microscopic and loss-on-ignition analyses. Major events are identified by the thickness of sand layers, presence of pebbles, marine shells and microfossils. Events of lesser magnitude are recognized by relatively thin clastic layers and finer grained sand or silt embedded in peat. However, in some intervals the recognition of individual storm deposits is more problematic due to the absence of interbedded peat layers, possibly due to erosion by subsequent storm events, resulting in the amalgamation of events. Such amalgamation is identified by the abrupt truncation of one fining-upward sequence and by the superposition of a younger sequence, commonly accompanied by visually obvious changes in structure, grain size and color/composition. Similar amalgamation of hurricane events has been observed in the Gulf of Mexico (Keen et al., 2004).

Correlation of hurricane events from core to core within and between transects was achieved by visual comparison in addition to lithological and organic (peat) contents determined from grain size and loss-on-ignition analyses. Not all transects show the same sequence of hurricane storm deposits. This is probably due to the variation in distance from the eyewall center, local topography and erosion patterns, and the peculiarities of the track and nature of individual storms. Here we detail cores from Gales Point and Mullins River, which represent a composite history of hurricane events for the past 5000 years.

4.1.1. Gales Point Line 1

The most seaward core (GP-12) of Gales Point Line 1 is 60 m from the ocean. GP-12 represents a typical core litholog in that loss-on-ignition data indicate a generally close correlation between low combustion ratio (e.g., absence of peat) and intervals of marine transported materials (e.g., sand, silt; Fig. 4). For most of the core the alternating peat and sand layers clearly mark depositional intervals of normal coastal vegetation alternating with storm transported marine material. In these intervals, hurricane deposits are easily identified and correlated landwards. At the bottom of the core, a sand layer ($<5\%$ organic content) shows evidence of three consecutive fining-upward sequences, each truncating the one below. This feature is interpreted as the amalgamation of three distinct hurricane events. Eight and possibly nine hurricane events can be identified in core GP-12 (Fig. 4). The numbering system is not sequential in this core because it is based on the composite number of storm events identified in the three transects. Some of the events are missing in GP-12, as well as in the other cores of this transect, possibly due to erosion by subsequent hurricanes, or the limited landward extent of some hurricane deposits.

The GP-12 core litholog can be correlated with the five landward cores, which follow a gradual slope of about 2° to a hardwood swamp where the last two cores (GP-15

Table 1
Radiocarbon dates of Gales Point Line 1 samples

Location	Depth (cm)	Material dated	^{14}C yr BP	Cal BP (2σ)	Probability (% area under distribution)
GP 13	107	Grass	2130±35	1998–2159	0.85
				2170–2177	0.01
				2246–2301	0.14
GP 20	74	Leaf	325±25	307–343	0.21
				346–464	0.79
GP 15	76	Wood	2200±30	2141–2324	1.00
GP 15	188	Wood	3990±45	4296–4331	0.04
				4348–4574	0.96
				4773–4777	0.002
GP 15	273	Leaf	4700±30	5321–5420	0.60
				5438–5481	0.23
				5531–5578	0.18

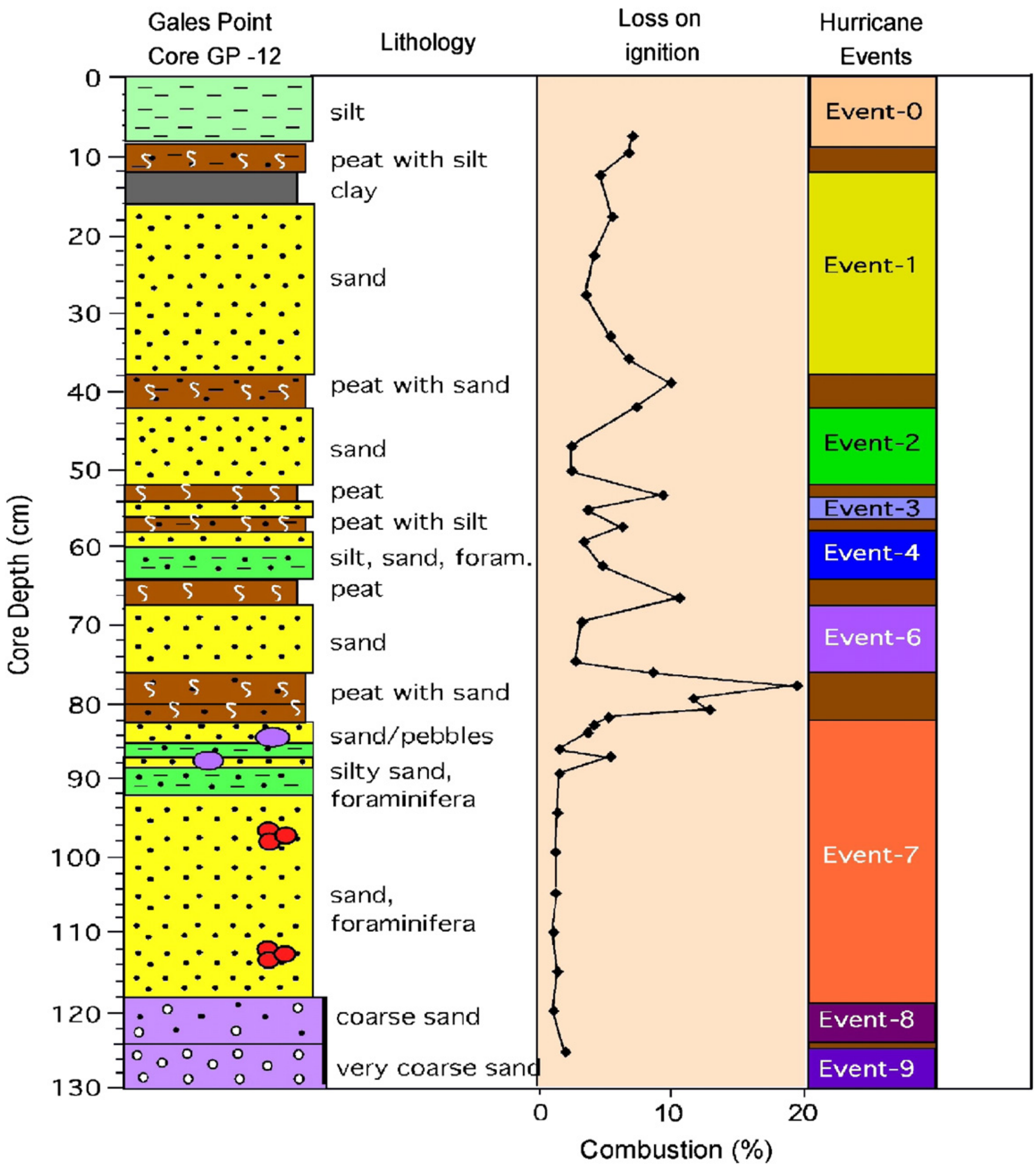

Fig. 4. Litholog and loss-on-ignition data for Core GP-12. Note that high combustion rates correspond to peat layers. The bottom sand interval is identified as three separate events on the basis of distinct structure, color and grain size.

and GP-16) were drilled at 100 and 110 m from the ocean (Fig. 5). The thickness of storm event layers and the grain size generally decrease with distance from the shoreline. Five radiocarbon dates derived from this transect provide age control for hurricane events.

At the top of core GP-12 is a silt layer (Event 0), which is not recognizable landward, but the underlying peat layer is present in all cores (Fig. 5). Event 1 is marked by a sand layer with foraminifera, which can be recognized in all of the six transect cores. The thickness of the sand layer decreases from 22 cm in GP-12 to a few cm in GP-16 and grain size decreases. Similarly, sand layers and grain size decreases are observed for all other events (Events, 2, 4, 6, 7, 8 and 9) with distance from shore. Storm Event 3 may be present in a 2 cm thick sand layer (54–56 cm) sandwiched between two peat layers. However, this sand layer could not be consistently differentiated landward from Event 4, a 6 cm thick sand and silt with foraminifera. For this reason Events 3 and 4 are left undifferentiated. Event 6 (68–76 cm core depth) marks a major hurricane. A radiocarbon age of $325 \pm 25\,^{14}$C yr BP (2σ dates from AD 1486–1643) was obtained from the 6 cm peat layer below Event 6 in GP-20 (Fig. 5). Event 7 is represented by a thick sand layer with pebbles and foraminifera (82–130 cm), which thin beyond 90 m from shore (Fig. 5). Event 8 is marked by a coarse sand layer below Event 7, but is separated by a peat layer between 90 and 110 m inland. The absence of the peat shoreward suggests erosion. A radiometric age of $2130 \pm 35\,^{14}$C yr BP was obtained for

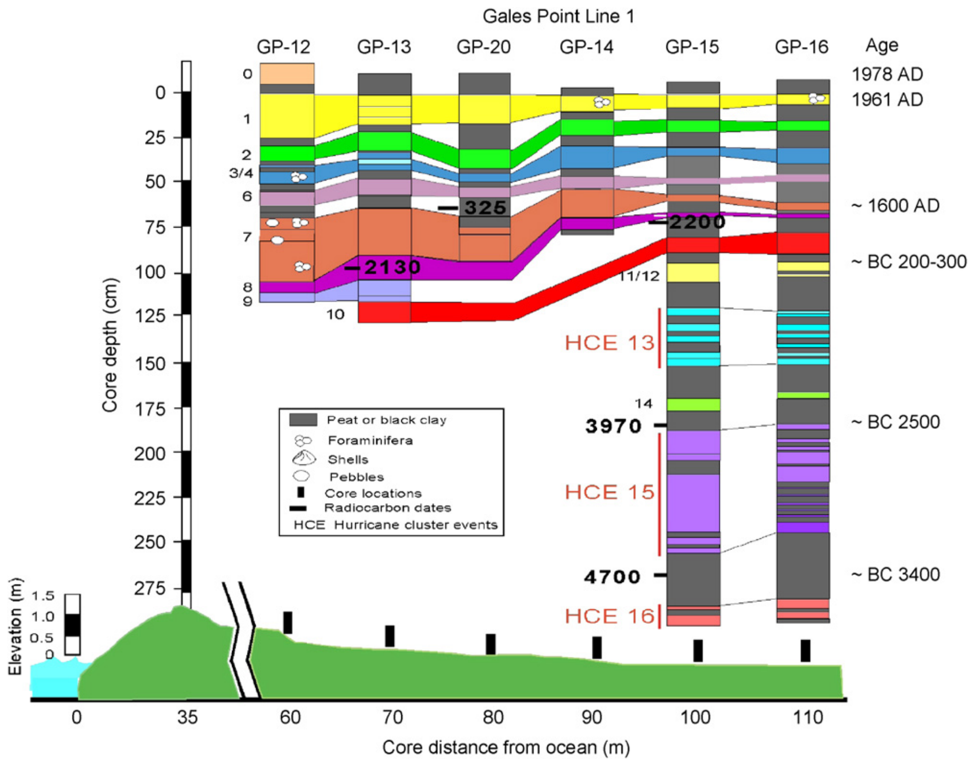

Fig. 5. Identification of hurricane events along Gales Point Line 1, based on stratigraphic correlation of event layers. The location of samples selected for radiocarbon dating are indicated by black bars. The dates, bold type, are in ^{14}C yr BP, with conversion to AD/BC on right side. HCE stands for hurricane cluster event.

Event 8 from a long grass stem in GP-13 (98–102 cm depth) that was presumably buried by the event. The peat underlying Event 8 in GP-15 yielded an age of 2200 ± 30 ^{14}C yr BP. Event 9 is marked by a coarse, pebbly sand layer (GP-12 and GP-13), but core recovery failed between 80 and 90 m landward. Event 10 is tentatively identified by a silt layer recovered in cores GP-13, GP-15, and GP-16.

The 3 m long cores (GP-15 and GP-16) recovered from the swamp depression consist mainly of peat with interlayers of silt marking storm events. In these cores, Events 11 and 12 are marked by two silt layers separated by peat in core GP-16, but not distinctly so in GP-15 (Fig. 5). A cluster of five to six closely spaced, thin, alternating silt, clay and peat layers mark a hurricane cluster event, HCE 13. Event 14 is a single event with a radiocarbon age of 3990 ± 45 ^{14}C yr BP from the underlying peat. Event HCE 15 is another cluster of hurricane events with at least 11 closely spaced clay and silt layers separated by peat or clayey peat in GP-16. Not all events of this cluster can be recognized in GP-15 due to mixing of clay and peat, possibly as a result of coring disturbance. Cluster Event HCE 16 is at the base of the core. The peat layer between cluster events HCE 15 and HCE 16 yielded a radiocarbon age of 4700 ± 30 ^{14}C yr BP (Fig. 5).

4.1.2. Mullins River Line 1

Mullins River Line 1 reveals predominantly coarse and finer grained sand layers near-shore with a peat layer on top. Landward of 62 m, thick clay or peat layers alternate with thin silt or sand layers, representing storm deposits (Fig. 6). In the most distant cores (105 and 120 m), drilled in a palmetto swamp, the storm deposits are generally thinner. Event 1 is marked by a thick sand unit with pebbles near-shore (core MR-1), but rapidly thins landward, similar to Events 2–4. These are tentatively identified as the same numbered events as at Gales Point. From 62 to 120 m inland Events 1–6 are recognized by relatively thin sand layers, frequently with pebbles up to 75 m inland. Event 6 shows a thicker sand layer landward of 90 m, which may be due to the local topographic depression, particularly in core MR-4. As at Gales Point, Event 7 represents the highest energy hurricane deposit characterized by thick orange-brown sand layers with pebbles and clasts ripped from the underlying clay. Large pebbles were transported at least 90 m inland. The cores in the palmetto swamp did not reach this deposit.

4.1.3. Mullins River Line 2

Mullins River Line 2 is located 75 m south of Line 1 and spans from 15 to 85 m inland, ending in the palmetto swamp that begins at about 70 m. This transect reveals a very different subsurface pattern from the nearby Line 1 or Gales Point (Fig. 7). Hurricane Event 1 shows significant spatial variability as indicated by the difference in thickness between 15 and 25 m from shore, absence between 37 and 45 m, thin layers between 55 and 65 m, and thick deposits in the palmetto swamp at 69 m. This variability appears to be the result of erosion and non-linear distribution of sediments by

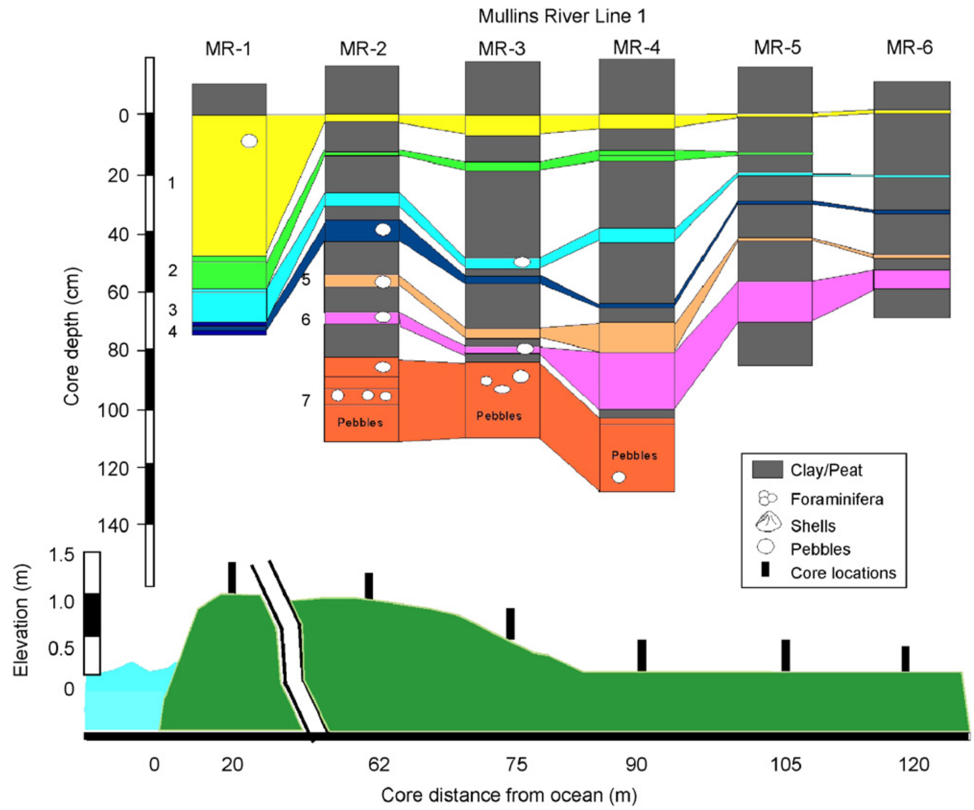

Fig. 6. Identification of hurricane events along Mullins River Line 1 based on stratigraphic correlation of event layers.

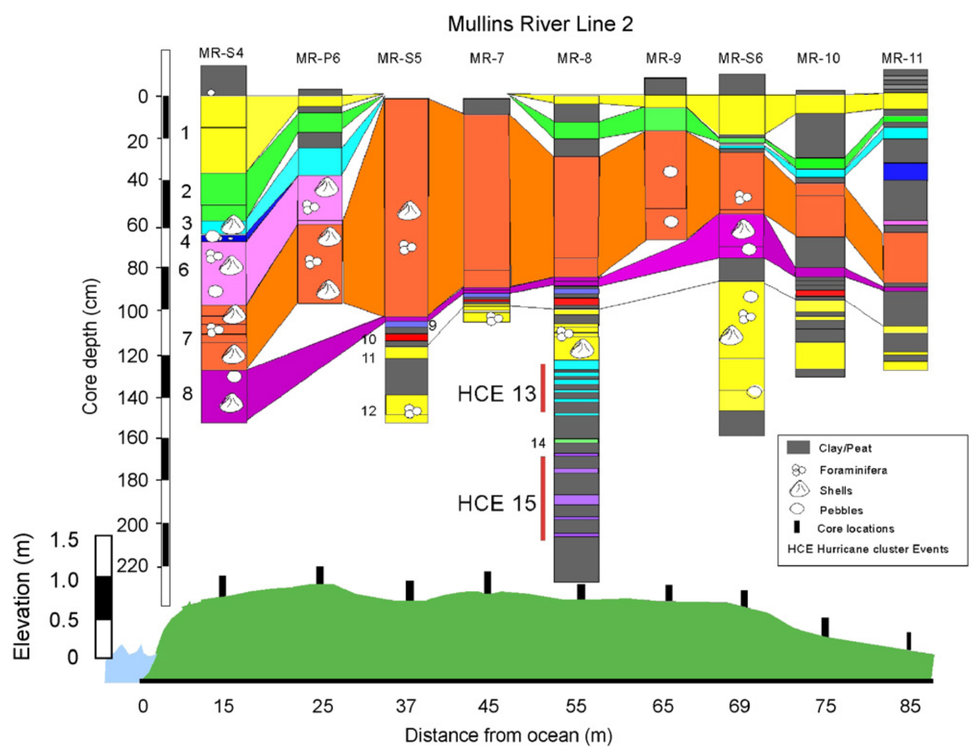

Fig. 7. Identification of hurricane events along Mullins River Line 2 based on stratigraphic correlation of event layers.

the storm. Between 37 and 45 m inland a significant amount of surface sediments was scoured, exposing Event 7 deposits. A local survivor noted that Hurricane Hattie "scooped out" the surface sediments at this locality. Events 2–4 and 6–8 can be recognized in core MR-S4 and Events 2, 3, 6 and 7 in core MR-P6. From 55 and 69 m inland, Event 2, and Events 3 and

4 are present, respectively. Event 6 is marked by a 30 cm thick sand, pebble and shell layer with foraminifera (Fig. 7). Event 7 is the most remarkable storm deposit encountered in all transects, but at Mullins River Line 2 this event is represented by an unusually thick coarse sand, shell and pebble layer with foraminifera that can be traced into the palmetto swamp (Fig. 7). Event 8 is recognized by a sand layer. Events 9 and 10 are tentatively identified by thin sand and silt layers separated by clay or peat. The sand layers of Events 11 and 12 are rich in shells, foraminifera and occasional pebbles, similar to Gales Point (Fig. 5). Cluster event CE 13 and CE 15 can be recognized, as well as Event 14.

4.2. *Geomorphic stability*

Sand layers identified as hurricane deposits can be traced inland, where with increasing distance from the shore the thickness of the sand layers and the grain size markedly decreases from coarse sand to finer sand and silt for each hurricane event (Figs. 5–7). Despite a core spacing of only 10 m some variability exists in the thickness of individual sand/silt layers along each transect. This may be due to local topographic highs and lows, erosion, differential sediment dumping, and differential compaction due to sediment burial, particularly in peat layers. The composition of sediments indicates that very little geomorphological change (e.g., lateral movement of the shoreline, creation/reduction of beach ridges and tidal inlets, etc.) occurred over the period under consideration.

For example, at the greatest distance from the shoreline along Gales Pont Line 1, cores GP-15 and GP-16 consist of swamp vegetation (peat) throughout, whereas shoreward cores GP-12, GP-13, GP-20, and GP-14 consistently indicate near-shore environments. Similar observations can be made in the other transects. This environmental stability probably results from the presence of the barrier reef system. During normal conditions, such a barrier reef results in very low-energy inner-reef environments, while during storms the reef's vertical seaward face and massive structure absorbs large amounts of wave energy, as well as causing earlier wave translation and reducing the fetch of waves over the inner channel, all of which act to reduce the destructive force of storms on the mainland (Hopley, 1984). These processes tend to produce geomorphologically stable reflective beach environments, since the force of both the normal and extreme weather conditions are reduced. Although erosion does occur, the long-term records of the Belize coast are not subject to the same level of geomorphological changes as those from less protected beach environments along the US Gulf and Atlantic coasts.

5. Discussion

5.1. *Hurricanes and the historical record*

All three transects in the Gales Point/Mullins River area show similar hurricane patterns. Relatively evenly spaced events are preceded by the much larger Event 7, which is characterized by thicker sedimentary deposits with larger grain sizes, pebbles and often-abundant marine fauna (Figs. 5–7). The two longest cores, (GP-15 and GP-16), show evidence of cyclic periods of increased hurricane activity. Sediment erosion prevents determination of average sedimentation rates and hence the extrapolation of hurricane event dates. However, the dates for some of the hurricanes can be inferred from ^{14}C dates and the historical hurricane records. Since radiocarbon dates were obtained only from Gales Point Line 1, the correlation with Mullins River is based on the stratigraphic sequence of events and the comparison of sedimentary characteristics (lithology, grain size, marine fossils). Not all events are recorded in all transects, and the number of events above Event 7 varies from 5 to 6 among the three transects

Event 0, found only at the top of the most seaward core of the Gales Point transect is tentatively identified as Hurricane Greta in 1978, which made landfall about 15 km to the south near Dangriga. The sand layer labeled Event 1 is probably the result of Hurricane Hattie (1961), as it is the topmost event layer at the site of eyewall impact for this category 4 storm. Event 2 can be stratigraphically correlated with the unnamed hurricane of 1931, though no absolute dating is available for the underlying interval.

Correlations between events lower in the column and historically recorded storms are problematic due to the vagueness of the historical record, which not only fails to note point of landfall, but also fails to register maximum wind speed, and, in general, merely records the strength of storms at the major population center, Belize City. Hence discrepancies between the sedimentary and historical records are likely, as storms that made landfall south of Belize City could have left a sedimentary signature in the study sites, but may not have been recorded historically. Alternatively, some of the hurricanes historically recorded at Belize City may have been too weak or too distant to have left a clear sedimentary record farther south at the study sites.

If the widely recognized Event 3 corresponds to a historically recorded hurricane, it is most likely the unnamed hurricane of 1893, which caused severe damage in Belize City and in the southern districts (Metzgen and Cain, 1925). Event 4 is weakly recorded or mixed with Event 3 throughout Gales Point Line 1, recognizable as a thin layer throughout Mullins River Line 1, and intermittently recorded in Mullins River Line 2. This possibly represents the storm of August 31, 1864, which passed directly over Belize City, causing a storm surge of 5 ft (Tannehill, 1938).

Event 5 is identifiable only in Mullins River Line 1, where it is present in all cores that reach sufficient depth. Stratigraphically, this storm can be correlated to the hurricane of August 19, 1827, which "drove all ships on shore at Belize" (Smith, 1842, quoted in Stoddart, 1963). Since this storm predates NOAA records, the location of landfall and maximum wind speed are unknown, prohibiting a more conclusive identification.

Event 6 is present across all cores in Mullins River Line 1 that are deep enough, and in all but the most landward core of Gales Point Line 1. It is also intermittently present in Mullins River Line 2. This event was relatively forceful, as indicated by pebbles found at 62 and 75 m inland in Mullins River Line 1, and pebbles, shells and foraminifera at 15 and 25 m in Mullins Rivers Line 2. Based on Stoddart's list (1963), the first recorded hurricane, which occurred on September 2, 1787, was the most powerful of the early storms, producing a 7–8 ft storm surge, which "desolated" Belize City, killing many people, destroying all shipping, and all but one house. Since the point of landfall is unknown, it is difficult to calculate the expected sedimentary impact of this storm at the coring locations.

5.2. An extreme event

The most noticeable hurricane is Event 7. Although this event could not be directly dated, a sample from 10 cm above it has a radiocarbon date of $325 \pm 25\ ^{14}C$ yr BP, for which the 2σ date ranges correspond to calendar dates for the periods AD 1486–1604 and 1607–1643. In the absence of other dating methods (e.g., average sedimentation rate), Event 7 can be tentatively dated to about AD 1500, assuming that the 10 cm of intervening sediment represents a significant, though undetermined, time span.

A date of $2130 \pm 35\ ^{14}C$ yr BP (2σ date ranges correspond to the periods cal BC 352–297, 228–221, and 210–49) was obtained for Event 8 sand deposits, which immediately underlie Event 7 (Fig. 5). These two ^{14}C dates thus indicate a large gap in the sediment record spanning about 1750 years, (from ~AD 1500 to ~250 BC) as a direct result of sediment erosion by Event 7. This suggests that Event 7 was catastrophic and removed significant amounts of surface sediments in the area of Gales Point and Mullins River. The extreme force of Event 7 is also indicated by the thickness of the deposited layers, the transport of large pebbles and shells, and the tearing of clasts from the underlying clay.

The magnitude of Event 7 is best viewed in relation to Hurricane Hattie (1961), (Event 1) whose point of eyewall impact at Mullins River (Stoddart, 1963) left a much less dramatic sedimentary profile (Figs. 5–7). Nevertheless, Hurricane Hattie was one of the defining events in modern Belize history. It caused tremendous physical damage and is historically important both socially and economically in that the British government moved the colony's capital from its traditional coastal location in Belize City to the present inland site at Belmopan in order to avoid similar disasters in the future (Setzekorn, 1978).

The location of landfall for Event 7 is not known and will have to be determined by future coring. However, its thick sedimentary deposits in the Gales Point and Mullins River areas leave no doubt as to the tremendous force of this hurricane, which exceeds any other in the 5000 year history examined. Although in the coastal areas of the United States the thickness of overwash layers as a proxy for storm magnitude is dependent upon the stage of the tide at time of landfall, this is not a factor in Belize with an average tidal range of ~0.3 m (Stoddart, 1962). Many factors, such as duration of landfall, angle of strike, coastal profile and geomorphology, and height and composition of beach barrier, can contribute to the sedimentary effect of a storm. Certainly, extent of the deposited sand layer cannot be uncritically used to determine absolute intensity. With several different proxies (grain size of transported material, thickness of deposit, amount of associated erosion, mixing of the underlying layer) over three transects spanning 4.5 km all indicating an extreme event, it seems highly likely that Event 7 was much stronger than all other storms in the record.

5.3. Clustered hurricane events

The sedimentary record extending to ~5000 ^{14}C yr BP was recovered in Gales Point cores GP-15 and GP-16 (Fig. 5). These two cores reveal a clustering of hurricane events separated by relatively long periods of quiet peat deposition. Within each cluster the rapidly alternating peat and clay/silt/sand layers probably indicate periods of greatly increased hurricane activity. The same clustered events can be recognized in the deepest Mullins River core (MR-8; Fig. 7).

In general, core GP-16, situated 10 m farther into the swamp, presents a higher resolution record than GP-15, with a minimum of six events for HCE 13, 11 events for HCE 15 and two events for HCE 16. The improved resolution of core GP-16 is presumably due to the reduced amalgamation of the hurricane layers resulting from the increased buffering provided by the additional 10 m of swamp vegetation.

A radiocarbon date obtained from 3 cm above the top of cluster HCE 15 in core GP-15 (Fig. 5) provided a date of $3990 \pm 45\ ^{14}C$ yr BP, which calibrates to a number of calendar dates centered around 4500–4400 cal yr BP. A second radiocarbon sample selected 15 cm below the bottom of HCE 15 provided a date of $4700 \pm 30\ ^{14}C$ yr BP, which calibrates to a number of calendar dates centered around 5500–5400 cal yr BP. These ^{14}C dates indicate that the cluster HCE 15 was deposited over a period of somewhat less than 1000 years between ~4500 and 4000 ^{14}C yr BP (~5500–4500 cal yr BP). The interval covered by HCE 13 indicates a somewhat shorter time period. Lack of bracketing dates prevents precise dating of this interval, but a period of ~3200–2500 ^{14}C yr BP can be estimated. This indicates two separate periods of increased hurricane activity occurring between ~4500 and 2500 ^{14}C yr BP (~5500–2500 cal yr BP).

5.4. Sea-level rise

Relative sea-level rise is an important factor when considering paleotempestological data, particularly in an area such as Belize characterized by a shallow, low gradient continental shelf, where a rapid rise results in a large transgression of the paleoshoreline. Many sea-level studies have been conducted in the Caribbean (e.g., Hendry, 1982; Lighty et al, 1982; Digerfeldt and Enell, 1984; Digerfeldt and Hendry, 1987; Fairbanks, 1989) and several are based on data from Belize (Woodroffe, 1988; Macintyre et al, 1995, 2003; Toscano and Macintyre, 2003). These studies generally show a smooth curve, with a decreased rate of rise around 5000–6000 cal yr BP. In Belize, the rate of relative rise varies latitudinally, with the deeper southern shelf locations displaying rates up to 1 m over the last 1000 years (McKillop, 1995, 2002). In contrast, in the north studies show a rise of only 30 cm over the last 2100 years, with present levels reached ~1000 ^{14}C yr BP (Mazullo et al., 1992; Dunn and Mazullo, 1993). This difference probably results from greater subsidence in the southern areas due to increased water depth and thus a strengthened hydrostatic response and earlier flooding which resulted in thicker peat deposition, and, consequently, greater compaction and dewatering.

Based on the northern curve established by Dunn and Mazullo (1993) (Fig. 8), change in relative sea level should have been fairly insignificant for the last 5000 years, although between 3500 and 5000 ^{14}C yr BP the impact would depend on the coastal gradient. Indeed, Peltier's mathematical model (1988) predicts levels slightly higher than the present for Belize over the past 5000 years.

5.5. Tsunamis

A related issue is the possibility of tsunami driven surges, which could mimic the sedimentary effects of a hurricane. Contradictory sedimentary differences between tsunami and hurricane deposits have been noted (Nanayama et al., 2000; Tuttle et al., 2004), making definitive differentiation between the two difficult (Donnelly, 2005). Belize lies just to the north of the junction of the Caribbean and North American Plates (Donnelly et al, 1990). The subduction of the North American Plate under the Caribbean Plate along the extreme southeast edge of the Caribbean results in the Antillean Island Arc, which includes several active volcanoes (Peter and Wertbrook, 1976; Paul, 1995) and recurrent seismic activity. A recent work catalogues 127 Caribbean tsunamis during the period 1498–1998 (O'Loughlin and Lander, 2003), resulting from a number of causes, including tectonically driven earthquakes, volcanic explosions, and subaerial and submarine slumping (Scheffers et al., 2005).

However, near Belize, situated >3000 km northwest of the island arc, the plate junction occurs as a strike/slip fault, resulting in lateral movement between the plates. This reduces the possibility of locally generated tsunamis primarily to those resulting from large-scale underwater slumping, the secondary effect of seaquakes. The possibility of teletsunamis (tsunamis generated >1000 km from the area of impact) is low, since those originating in the Antillean Island Arc are relatively small (Scheffers et al., 2005), and an investigation of Holocene tsunami deposits in the southern Caribbean excludes tsunamis approaching from the open Atlantic as a probable cause (Scheffers et al., 2005). Therefore, the frequency of tsunamis near Belize is low, with only three being recorded since 1498. All three were generated along the Honduran coast, with the 1856 event, apparently the strongest, affecting only the southernmost tip of Belize (McCann and Pennington, 1990; O'Loughlin and Lander, 2003). Thus, although the possibility exists that one or more of the suspected hurricane-generated layers actually result from tsunamis, the probability is low.

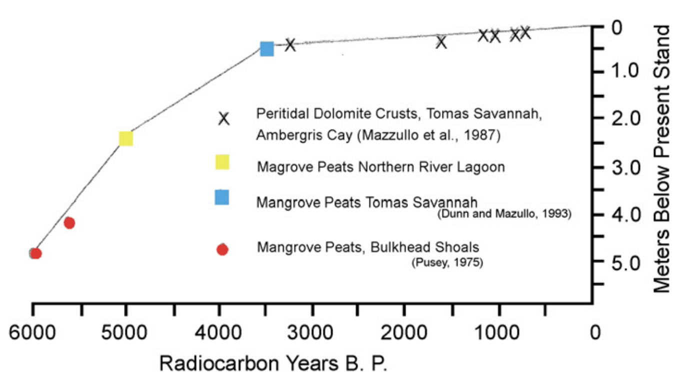

Fig. 8. Sea-level curve for northern Belize, modified from Dunn and Mazullo (1993).

5.6. Annual hurricane strike probability

An estimate of the average annual hurricane strike probability can be made based on the ^{14}C dates. The ^{14}C date of 325±25 ^{14}C yr BP obtained from between Events 6 and 7 in core GP-20 corresponds to calendar date ranges from AD 1486–1604 (78.6% probability) and AD 1607–1643 (21.4% probability). Five and six hurricane events are recorded after that time at Gales Point and Mullins River, respectively. This indicates that the minimum average annual probability of recordable strikes is ~1–1.2% (five to six storms in ~500 years). However, to arrive at an accurate risk assessment for the national coastline the relationship between strikes occurring and strikes recorded must be determined. Cores obtained from the point of eyewall impact of Hurricane Greta (category 3, 1978) displayed only a weak, spatially confined sedimentary signal, while cores from the point of landfall of Hurricane Iris (category 4, 2001) failed to display clear sedimentary evidence of the storm. This indicates that perhaps the threshold for reliable recordation might be as high as a strong category 4.

Another important parameter is the radius within which storms are recorded. Examination of cores from a location ~15 km to the south (not shown) shows very little correspondence with the events recorded in the Mullins River/Gales Point area. Because the coastline of Belize extends ~250 km north–south, a recordation radius of 15 km (recordation diameter 30 km) results in a national exposure eight times larger than that of each individual location, assuming uniform geographic strike frequency. Based on the historical data that hurricane strike frequency increases south to north for Belize (Alaka, 1976), a probability calculation derived from the central area should be reasonably applicable for the entire coast.

These observations suggest a national exposure of roughly 8–10 major storms (category 3 or larger) every century, or roughly one per decade. This is only slightly higher than the 20th century record. Stoddart (1963) lists 13 hurricanes from 1900 through Hattie in 1961, five of which caused serious economic damage. To this list must be added the minor hurricanes Francelia (1969) and Fifi (1974), along with Greta in 1978, for a total of 16. The NOAA record, though differing substantially from Stoddart's before 1942, records 13 hurricanes for the 1900s, five of them major hurricanes. Not included in either list for the 1900s are direct hits by two major hurricanes (Keith, 2000; Iris, 2001), as well as near misses by two category 5 storms, the extremely large Mitch (1998) and Dean (2007).

Complicating this calculation are the uncertainties regarding the sensitivity of the recording sites. Other studies have identified hurricanes over larger distances, based on the presence of marine microfossils (Collins et al., 1999; Scott et al., 2003). The reduced recordation diameter indicated here might be due to specific characteristics of either the sites of impact for Greta and Iris or the storms themselves. Possibilities include a low percentage of clastic material in the transported material (local informants complained of the odor of the material deposited by Iris, indicating a high organic content, rather than sand) and the unsuitability of micropaleontological analysis as a diagnostic tool as calcareous materials dissolve rapidly in the acidic swamp environments (Graham, 1994, p. 27).

5.7. Cyclicity in hurricane frequency

Liu and Fearn (2000) hypothesize a millennial scale oscillation in the cycle of North Atlantic hurricane activity. Based on results from a variety of sites on the US Gulf Coast, they identify a period of hyperactivity there from around ~3400–1000 ^{14}C yr BP, with periods of greatly reduced activity before and after. They have proposed shifts in the position of the Bermuda High as the causative agent of this oscillation, as over the historical period the strength/position of the Bermuda High has been shown to exert important control over location of hurricane landfall (Elsner et al., 2000). A high-resolution record based on varved sediments from the Cariaco Basin in the southern Caribbean has demonstrated significant low frequency meridional movement in the Intertropical Convergence Zone (ITCZ) over the past 14,000 years (Haug et al., 2001). If strong north/south migration of the ITCZ is accompanied by similar, if not precisely simultaneous, movements of the Bermuda High and the hurricane zone, periods of increased hurricane activity in the Caribbean should exhibit latitudinal clustering (McCloskey and Knowles, in press).

An investigation from St. Martin in the French West Indies (Bertran et al., 2004) suggests increased hurricane activity there for the period 4900–~2600 cal yr BP, closely matching the record from this study, (two periods of increased activity from ~5500 to 2500 cal yr BP). Both sites are at the same latitude (~18°N), thereby supporting the hypothesis of latitudinally coherent periods of increased hurricane activity. Furthermore, this period correlates to a period of generally southern migration of the ITCZ, while the period of hyperactivity observed by Liu and Fearn (2000) on the Gulf Coast roughly correlates to a northern movement of the ITCZ (Haug et al., 2001). This evidence, therefore, supports the idea of a climatically controlled zone of hurricane landfall slowly migrating north and south across the Caribbean. Since the position of the Bermuda High also has significant climatic implications, especially precipitation levels, the influence of such a migration on cultural development is potentially of regional importance.

However, Donnelly and Woodruff (2007) show a different pattern of hurricane activity from sediment cores in Puerto Rico. They observed increased activity from ~5400 to 3600, decreased activity for the period ~3600–2500 cal yr BP, and increased activity again 2500–1000 cal yr BP, and 250 cal yr BP to the present. Because the most recent active period corresponds to relatively cool sea surface temperatures (SST), they conclude that warm SST are not necessary for increased hurricane activity. Coherent and interrelated atmospheric conditions, such as the El Nino/Southern Oscillation (ENSO) and the condition of the West African monsoon, they suggest, exert a more important influence over hurricane landfall than isolated conditions such as steering control and average SST. Based on data for the period 1950–2004, Bell and Chelliah (2006) make a similar argument for a coherent coupling of oceanic and atmospheric conditions as the driver of hurricane activity. Latitudinal shifts in the atmospheric circulation system could be the proximate cause of such a coherent system (McCloskey and Knowles, in press). Further studies covering a larger number of localities along with the use of new investigative methods, such as isotopic investigation of tree ring and speleothems records (Miller et al., 2006; Frappier et al., 2007a, b) may help resolve this issue.

5.8. Hurricanes and the ancient Maya

Several recent studies have linked cultural development of the ancient Maya with environmental conditions, in particular correlating demographic and cultural decline with periods of drought (Hodell et al., 1995, 2001; Curtis and Hodell, 1996; Gill, 2000; Islebe and Sanchez, 2002; Rosenmeier et al., 2002; Haug et al., 2003), perhaps related to the 206 year solar activity cycle (Hodell et al., 2001), or changes in the intensity of the earth's geomagnetic field (Gallet and Genevey, 2007). It is possible that hurricanes also exerted an important environmental control.

Certainly, the cultural, economic and agricultural destruction associated with major hurricane strikes occurring at the frequency calculated here suggests the possibility of continuing restraint on the ancient Maya civilization.

Hurricanes would have severely affected the agricultural base since the hurricane season corresponds to the most vulnerable period of the annual agricultural cycle when the major corn crop is either growing or drying in the fields. A major hurricane strike during this period would have had very significant nutritional consequences, as a large percentage of the year's grain would have been lost due to the rapid spoiling of the corn resulting from storms leveling the fields. Although some portion of the crop could potentially be salvaged if immediately collected and dried, the effectiveness of this seems rather limited, particularly given the probability of continuing precipitation and the vulnerability of thatch roofs to wind damage. Only mature corn can be dried in this manner and requires being spread out in the sun, or husked, shelled and dried over a fire. If immature, the corn would be lost entirely. For example, such a devastating effect was observed in Honduras after the passage of Hurricane Mitch (1998), which destroyed 58% and 35% of the corn and bean crops, respectively (Economic Commission for Latin America and the Caribbean, 1999; Global Information and Early Warning System, 1999). In addition, stored food crops were lost to floods, landslides and damaged buildings (Morris et al., 2002). This threat to the national food security was severe enough to force the government to release strategic grain reserves (Mainville, 2003).

Even more important is the possible reduction of long-term agricultural resources. During periods of high population density that requires the utilization of hillsides and marginal land (McKillop, 2004; Beach et al., 2006) the extreme rainfall connected with hurricanes could have resulted in significant soil erosion and phosphorus burial, decreasing the area's long-term carrying capacity. Although the exact nature of ancient Maya agricultural practices is under debate (Fedick, 1996), it probably shared some characteristics with present day sustainable land management (SLM) practices. These utilize a variety of non-mechanized soil conservation and agroecological methods, including agroforestry, to promote agricultural sustainability on small holdings. Holt-Gimenez (2002) shows that relative to "conventional" farms, these practices reduced the environmental damage to farmlands, such as loss of topsoil and vegetation, landslides and erosion that were inflicted by Hurricane Mitch. However, he found that agroecological resistance "collapsed" under conditions of high stress related to extreme storm intensity. These findings combined with the widespread occurrence of landslides throughout Honduras and Nicaragua as a result of Hurricane Mitch suggest that major hurricanes could have negatively impacted ancient Maya agricultural potential on decadal to centennial timescales.

Some level of disruption of trade (particularly coastal) and overall economic stability seem implicit in large-scale hurricane strikes. Although these disruptions would have been both local and periodic, they could have resulted in chronic cultural stress. Our study suggests that several of the prehistoric hurricanes left a sedimentary signature roughly equal to, or exceeding that left by Hurricane Hattie at landfall. For prehistoric hurricanes, where the locations of landfalls and hence maximum sedimentary expressions are unknown, their sizes are likely underestimated in this study. The ability of large individual events to cause regional destruction was demonstrated by hurricane Katrina on the US Gulf Coast in 2005 and Hurricane Mitch in 1998, which resulted in an estimated 10,000 deaths, 3 million displaced or homeless people in Central America (Ecocentral, 1998; CRIES, 1999) and inflicted damages equal to 13.3% of Central America's GNP (Holt-Gimenez, 2002).

Of particular interest in this regard is the sheer magnitude of the extremely large prehistoric Event 7, which together with similar magnitude hurricanes could be expected to have caused devastating large-scale social disruptions. Unfortunately, sediment erosion by Event 7 removed the relevant interval that could have provided direct information concerning the relationship between hurricanes and the classic period (AD 300–900). During the subsequent collapse of the Maya civilization, lowlands in Mexico, Belize, Honduras, and coastal Guatemala were abandoned between AD 975 and 1000 (Coe, 1999).

The occurrence of multi-centennial periods of increased hurricane frequency, as suggested by clusters of events between ~4500 and 2500 ^{14}C yr BP, would have greatly increased the environmental stress, perhaps making coastal farming untenable. Future recovery of longer and more complete cores may reveal whether this clustering of events continued into the classic period, and if so, how these periods correlate with Maya cultural history.

6. Conclusions

1. Five to six major hurricanes were observed in the sedimentary record of the past 500 years along the central coast of Belize. This represents 1 to 1.2 catastrophic storms every 100 years in the study area. The "average" strike probability for the 250 km long coast of Belize is roughly one major storm per decade.
2. One giant hurricane, Event 7, struck the central coast of Belize sometime before AD 1500. Compared with Hurricane Hattie (category 4), Event 7 was significantly more powerful and capable of achieving catastrophic effects. Several other events appear to have been roughly equivalent to Hurricane Hattie.
3. A temporal clustering of hurricanes was observed in the study area. These periods of hyperactivity roughly match those determined for St. Martin, and precede a similar period for the US Gulf Coast. These records support a model of climatically controlled migration of the hurricane belt.

Acknowledgments

This study is the result of undergraduate thesis research conducted at Princeton University by T.A.M. The study was made possible by financial support from the Geosciences Department, the Princeton Environmental Institute, the Dean's Office and the Morris K. Udall Scholarship. Subsequent support was received from the Board of Regents Scholarship at Louisiana State University, and a National Science Foundation Graduate Research Fellowship. We are grateful to J.P. Donnelly for his generous advice and teaching T.A.M. the basics in coring for hurricane records, and Kam-biu Liu for discussions and guidance. We thank Ms. E. Wade, former Director, and Mr. Andre Cho, Director and Chief Geologist, of the Geology and Petroleum Department in the Ministry of Natural Resources, Belize, for their generous support with fieldwork, logistics and permits. We thank Rennick Jackson of Belize Fisheries and Cliff Vernon of the Belize Lands Department for their field assistance.

References

Alaka, M.A., 1976. Climatology of Atlantic tropical storms and hurricanes. In: Schwerdtfeger, W. (Ed.), Climates of Central and South America. World Survey of Climatology, vol. 12. Elsevier, New York, pp. 479–509.

Beach, T., Dunning, N., Luzzadder-Beach, S., Cook, D.E., Lohse, J., 2006. Impacts of ancient Maya on soils and soil erosion in the central Maya lowlands. Catena 65, 166–178.

Bell, G.D., Chelliah, M., 2006. Leading tropical modes associated with interannual and multidecadal fluctuations in North Atlantic hurricane activity. Journal of Climate 19, 590–612.

Bertran, P., Bonnissent, D., Imbert, D., Lozouet, P., Serrand, N., Stouvenot, C., 2004. Paleoclimat des Petites Antilles depuis 4000 BP: l'enregistrement de la lagune de Grand-Case a Saint-Martin. C.R. Geoscience 336, 1501–1510.

Chenoweth, M., 2006. A reassessment of historical Atlantic basin tropical activity, 1700–1855. Climatic Change 76, 169–240.

Chenoweth, M., 2007. Objective classification of historical tropical cyclone intensity. Journal of Geophysical Research-Atmospheres 112 (D5) Article No. D05101.

Coe, M.D., 1999. The Maya, sixth ed. Thames and Hudson, London.

Collins, E.S., Scott, D.B., Gayes, P.T., 1999. Hurricane records on the South Carolina Coast: can they be detected in the sediment record? Quaternary International 56, 15–26.

Coordinadora Regional de Investigaciones Económicas y Sociales (CRIES), 1999. Enfoque estrategico centroamericano sobre reconstrucción y transformación desde la sociedad civil organizada nacional y regionalmente. CRIES, Managua.

Curtis, J.H., Hodell, D.A., 1996. Climate variability on the Yucatan peninsula (Mexico) during the past 3500 years, and the implications for Maya cultural evolution. Quaternary Research 46, 37–47.

Dean, W.G., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. Journal of Sedimentary Petrology 44, 242–248.

Digerfeldt, G., Enell, M., 1984. Paleoecological studies of the past development of the Negril and Black River morasses, Jamaica. Petrol Corp Jamaica, Kingston, Jamaica.

Digerfeldt, G., Hendry, M.D., 1987. An 8000 year Holocene sea-level record from Jamaica: implications for interpretation of Caribbean reef and coastal history. Coral Reefs 5, 165–169.

Donnelly, J.P., 2005. Evidence of past intense tropical cyclones from backbarrier salt pond sediments: a case study from Isla de Culebrita, Puerto Rico, USA. Journal of Coastal Research 42, 201–210.

Donnelly, J.P., Woodruff, J.D., 2007. Intense hurricane activity over the past 5000 years controlled by El Nino and the West African monsoon. Nature 447, 465–468.

Donnelly, T.W., Horne, G.S., Finch, R.C., Lopez-Ramos, E., 1990. Northern Central America; the Maya and Chortis blocks. In: Dengo, G., Case, J.E. (Eds.), The Geology of North America. Vol. H, The Caribbean Region. The Geologic Society of America, Boulder, CO, pp. 37–76.

Donnelly, J.P., Bryant, S., Butler, J., Dowling, J., Fan, L., Hausmann, N., Newby, P., Shuman, B., Stern, J., Westover, K., Webb, T., 2001a. 700 year sedimentary record of intense hurricane landfalls in southern New England. GSA Bulletin 113, 714–727.

Donnelly, J.P., Roll, S., Wengren, M., Butler, J., Lederer, R., Webb, T., 2001b. Sedimentary evidence of intense hurricane strikes from New Jersey. Geology 29, 615–618.

Donnelly, J.P., Butler, J., Roll, S., Wengren, M., Webb, T., 2004. A backbarrier overwash record of intense storms from Brigantine, New Jersey. Marine Geology 210, 107–121.

Dunn, R.K., Mazullo, S.J., 1993. Holocene Paleocoastal reconstruction and its relationship to Marco Gonzales, Ambergris Caye, Belize. Journal of Field Archaeology 20, 121–131.

Ecocentral, 1998. Hurricane Mitch kills 11,000, wrecks region's economy. In: Noticen, 1998-11-12. 〈http://ladb.unm.edu/noti〉.

Economic Commission for Latin America and the Caribbean, 1999. Nicaragua: assessment of the damage caused by Hurricane Mitch 1998. Implications for Economic and Social Development and for the Environment, ECLAC, Mexico.

Elsner, J.B., Liu, K.-B., Kocher, B., 2000. Spatial variations in major US hurricane activity: statistics and a physical mechanism. Journal of Climate 13, 2293–2305.

Fairbanks, R.G., 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature 342, 637–642.

Fedick, S.L. (Ed.), 1996. The Managed Mosaic: Ancient Maya Agriculture and Resource Use. University of Utah Press, Salt Lake City.

Frappier, A.B., Sahagian, D., Carpenter, S.J., González, L.A., Frappier, B.R., 2007a. A stalagmite proxy record of recent tropical cyclone events. Geology 7, 111–114.

Frappier, A.B., Knutson, T., Liu, K.-B., Emanuel, K., 2007b. Perspective: coordinating paleoclimate research on tropical cyclones with hurricane-climate theory and modeling. Tellus Series A—Dynamic Meteorology and Oceanography 59 (4), 529–537.

Gallet, Y., Genevey, A., 2007. The Mayans: climate determinism or geomagnetic determinism? EOS 88 (11), 129–130.

Garcia-Herrera, R., Gimeno, L., Ribera, P., Hernandez, E., Gonzalez, E., Fernandez, G., 2007. Identification of Caribbean hurricanes from Spanish documentary sources. Climatic Change 83, 55–85.

Gill, R.B., 2000. The Great Maya Droughts. University of New Mexico Press, Albuquerque.

Global Information and Early Warning System, 1999. Special Report on Honduras. FAO/WFP Crop and Food Supply Assessment Mission to Honduras.

Graham, E., 1994. The Highlands of the Lowlands: Environment and Archaeology in the Stann Creek District, Belize, Central America. Monographs in World Archaeology No. 19. Prehistory Press, Madison, WI.

Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., Rohl, U., 2001. Southward migration of the intertropical convergence zone through the Holocene. Science 292, 1304–1314.

Haug, G.H., Gunther, D., Peterson, L.C., Sigman, D.M., Hughen, K.A., Aeschlimann, B., 2003. Climate and the collapse of Maya civilization. Science 299, 1731–1735.

Hendry, M.D., 1982. Late-Holocene sea-level changes in western Jamaica. In: Colquhuon, D.J. (Ed.), Holocene Sea-Level Fluctuations: Magnitude and Causes. University of South Carolina, Columbia, SC, pp. 71–80.

Hodell, D.A., Curtis, J.H., Brenner, M., 1995. Possible role of climate in the collapse of Classic Maya civilization. Nature 375, 391–394.

Hodell, D.A., Brenner, M., Curtis, J.H., Guilderson, T., 2001. Solar forcing of drought frequency in the Maya lowlands. Science 292, 1367–1370.

Holt-Gimenez, E., 2002. Measuring farmers' agroecological resistance after Hurricane Mitch in Nicaragua: a case study in participatory, sustainable land management impact monitoring. Agriculture Ecosystems and Environment 93, 87–105.

Hopley, D., 1984. The Holocene "high energy window" on the central Great Barrier Reef. In: Thom, B.G. (Ed.), Coastal Geomorphology in Australia. Academic Press, Sydney, pp. 135–150.

Islebe, G.A., Sanchez, O., 2002. History of Late Holocene vegetation at Quintana Roo, Caribbean coast of Mexico. Plant Ecology 160, 187–192.

James, N.P., Ginsburg, R.N., 1979. The Seaward Margin of Belize Barrier and Atoll Reefs. International Association of Sedimentologists, Special Publication No. 3.

Keen, T.R., Bentley, S.J., Vaughan, W.C., Blain, C.A., 2004. The generation and preservation of multiple hurricane beds in the northern Gulf of Mexico. Marine Geology 210, 79–105.

Lighty, R.G., Macintyre, I.G., Stuckenrath, R., 1982. Acropora Palmata reef frameworks: a reliable indicator of sea level in the western Atlantic for the past 10,000 years. Coral Reefs 1, 125–130.

Liu, K-B., Fearn, M.L., 1993. Lake-sediment record of late Holocene hurricane activities from coastal Alabama. Geology 21, 793–796.

Liu, K.-B., Fearn, M.L., 2000. Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records. Quaternary Research 54, 238–245.

Macintyre, I.G., Littler, M.M., Littler, D.S., 1995. Holocene history of Tobacco Range, Belize, Central America. Atoll Research Bulletin 430, 1–18.

Macintyre, I.G., Toscana, M.A., Lighty, R.G., Bond, G.B., 2003. Holocene History of the Mangrove Islands of Twin Cays, Belize, Central America. Atoll Research Bulletin 510.

Mainville, D.Y., 2003. Disasters and development in agricultural input markets: bean seed markets in Honduras after Hurricane Mitch. Disasters 27, 154–171.

Mazullo, S.J., Anderson-Underwood, K.E., Burke, C.D., Bischoff, W.D., 1992. Holocene coral patch reef ecology and sedimentary architecture, northern Belize, Central America. Palaios 7, 591–601.

McCann, W.R., Pennington, W.D., 1990. Seismicity, large earthquakes, and the margin of the Caribbean Plate. In: Dengo, G., Case, J.E. (Eds.), The Geology of North America, Vol. H, The Caribbean Region. The Geologic Society of America, Boulder, CO, pp. 291–306.

McCloskey, T.A., Knowles, J.T., in press. Migration of the tropical cyclone zone throughout the Holocene. In: Elsner, J.B., Jagger, T.H. (Eds.), Hurricanes and Climate Change, Springer, New York.

McKillop, H., 1995. Underwater archaeology, salt production, and coastal Maya trade at Stingray Lagoon, Belize. Latin American Antiquity 6, 214–228.

McKillop, H., 2002. Salt: White Gold of the Ancient Maya. University Press of Florida, Gainesville, FL.

McKillop, H., 2004. The Ancient Maya: New Perspectives. ABC-CLIO, Santa Barbara, CA.

Metzgen, M., Cain, E.E., 1925. The Handbook of British Honduras Comprising Historical, Statistical and General Information Concerning the Colony. The West India Commission, London.

Miller, D., Moro, C.I., Grissino-Mayer, H.D., Mock, C.J., Uhle, M.E., Sharp, Z., 2006. Tree-ring isotope records of tropical cyclone activity. Proceedings of the National Academy of Science 103, 14294–14297.

Mock, C.J., 2004. Tropical cyclone reconstructions from documentary records; examples from South Carolina. In: Murnane, R.J., Liu, K.B. (Eds.), Hurricanes and Typhoons: Past, Present, and Future. Columbia University Press, New York, pp. 121–148.

Morris, S.S., Neidecker-Gonzales, O., Carletto, C., Munguia, M., Medina, J.M., Wodon, Q., 2002. Hurricane Mitch and the livelihoods of the rural poor in Honduras. World Development 30, 49–60.

Nanayama, F., Shigeno, K., Satake, K., Shimokawa, K., Koitabashi, S., Miyasaka, S., Ishii, M., 2000. Sedimentary differences between the 1993 Hokkaido-nansei-oki tsunami and the 1959 Miyakojima typhoon at Taisei, southwestern Hokkaido, northern Japan. Sedimentary Geology 135, 255–264.

Neumann, C.J., Jarvinen, B.R., McAdie, C.J., Hammer, G.R., 1999. Tropical cyclones of the North Atlantic Ocean, 1871–1998. 5th Revision. DOC/NOAA Historical Climatology Series 6-2. National Climate Data Center, Asheville.

O'Loughlin, K.F., Lander, J.F., 2003. Caribbean Tsunamis: A 500-year History from 1498–1998. Kluwer Academic Publishers, Cordrecht.

Paul, M., 1995. Geologic and tectonic development of the Caribbean plate boundary in southern Central America. Geological Society of America, Special Paper 295, XI–XXXII.

Peltier, W.R., 1988. Lithospheric thickness, Antarctic deglaciation history, and ocean basin discretization effects in a global model of postglacial sea level changes: a summary of some sources of nonuniqueness. Quaternary Research 29, 93–112.

Peter, G., Wertbrook, G.K., 1976. Tectonics of the southwestern North Atlantic and Barbados Ridge Complex. Bulletin of the Association of American Petroleum Geologists 60, 1078–1106.

Pielke Jr., R.A., Pielke Sr., R.A., 1997. Vulnerability to hurricanes along the US Atlantic and Gulf Coasts: considerations of the use of long-term forecasts. In: Diaz, H.F., Pulwarty, R.S. (Eds.), Hurricanes, Climate and Socioeconomic Impacts. Springer, Berlin/Heidelburg/New York, pp. 147–180.

Rappaport, E.N., Fernandez-Partagas, J., 1997. History of the deadliest Atlantic tropical cyclones since the discovery of the New World. In: Diaz, H.F., Pulwarty, R.S. (Eds.), Hurricanes, Climate and Socioeconomic Impacts. Springer, Berlin/Heidelburg/New York, pp. 93–108.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C., Blackwell, P.G., Buck, C.E., Burr, G., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hughen, K.A., Kromer, B., McCormac, F.G., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. Radiocarbon 46, 1029–1058.

Rosenmeier, M.F., Hodell, D.A., Brenner, M., Curtis, J.H., 2002. A 4000-year lacustrine record of environmental change in the southern Maya lowlands, Peten, Guatemala. Quaternary Research 57, 183–190.

Scott, D.B., Collins, E.S., Gayes, T.S., Wright, E., 2003. Record of prehistoric hurricanes on the South Carolina coast based on micropaleontological and sedimentilogical evidence, with comparison to other Atlantic Coast records. GSA Bulletin 115, 1027–1039.

Scheffers, A., Scheffers, S., Kelletat, D., 2005. Paleo-tsunami relics on the southern and central Antillean island arc. Journal of Coastal Research 21, 263–273.

Setzekorn, W.D., 1978. A Profile of the New Nation of Belize, Formerly British Honduras. Ohio University Press, Columbus, OH.

Short, A.D., Hesp, P.A., 1982. Wave, beach and dune interactions in southeastern Australia. Marine Geology 48, 259–284.

Smith, T., 1842. The East Coast of Yucatan. Nautical Magazine 11, 334–338.

Stoddart, D.R., 1962. Three Caribbean atolls: Turneffe Islands, Lighthouse reef, and Glover's reef, British Honduras. Atoll Research Bulletin 87, 1–147.

Stoddart, D.R., 1963. Effects of Hurricane Hattie on the British Honduran reefs and cays, October 30–31, 1961. Atoll Research Bulletin 95, 1–142.

Stuiver, M., Reimer, P.J., 1993. Radiocarbon 35, 215–230.

Tannehill, I.R., 1938. Hurricanes: Their Nature and History. Princeton University Press, Princeton.

Toscano, M.A., Macintyre, I.G., 2003. Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated C-14 dates

from Acropora palmate framework and intertidal mangrove peat. Coral Reefs 22, 257–270.
Tuttle, M.P., Ruffman, A., Anderson, T., Jeter, H., 2004. Distinguishing tsunami from storm deposits in Eastern North America; the 1929 Grand Banks tsunami versus the 1991 Halloween storm. Seismological Research Letters 75, 117–131.
Woodroffe, C.D., 1988. Mangroves and sedimentation in reef environments: indicators of past sea-level trends? In: Proceedings of the 6th International Coral Reef Symposium, Australia, vol. 6, pp. 535–539.
Wright, L.D., Short, A.D., 1984. Morphodynamic variability of beaches and surfzones: a synthesis. Marine Geology 56, 92–118.