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A decadally-resolved paleohurricane record archived in the late Holocene sediments of a Florida sinkhole

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ABSTRACT

A 4500-year record of hurricane-induced storm surges is developed from sediment cores collected from a coastal sinkhole near Apalachee Bay, Florida. Recent deposition of sand layers in the upper sediments of the pond was found to be contemporaneous with significant, historic storm surges at the site modeled using SLOSH and the Best Track, post-1851 A.D. dataset. Using the historic portion of the record for calibration, paleohurricane deposits were identified by sand content and dated using radiocarbon-based age models. Marine-indicative foraminifera, some originating at least 5 km offshore, were present in several modern and ancient storm deposits. The presence and long-term preservation of offshore foraminifera suggest that this site and others like it may yield promising microfossil-based paleohurricane reconstructions in the future. Due to the sub-decadal (~7 years) resolution of the record and the site's high susceptibility to hurricane-generated storm surges, the average, local frequency of recorded events, approximately 3.9 storms per century, is greater than that of previously published paleohurricane records from the region. The high incidence of recorded events permitted a time series of local hurricane frequency during the last five millennia to be constructed. Variability in the frequency of the largest storm layers was found to be greater than what would likely occur by chance alone, with intervals of both anomalously high and low storm frequency identified. However, the rate at which smaller layers were deposited was relatively constant over the last five millennia. This may suggest that significant variability in hurricane frequency has occurred only in the highest magnitude events. The frequency of high magnitude events peaked near 6 storms per century between 2800 and 2300 years ago. High magnitude events were relatively rare with about 0–3 storms per century occurring between 1900 and 1600 years ago and between 400 and 150 years ago. A marked decline in the number of large storm deposits, which began around 600 years ago, has persisted through present with below average frequency over the last 150 years when compared to the preceding five millennia.

1. Introduction

1.1. Review and motivation

The manner in which tropical cyclone activity and climate interact has critical implications for society and is not well understood. Meteorological records of the number, track and intensity of hurricanes in the Atlantic extend back to the mid-19th century, although debate exists over whether trends in storm observations genuinely reflect secular changes in the underlying population of Atlantic hurricanes or if advances in storm detection and observation prevent the attribution of these trends to changes in storm climate (Goldenberg et al., 2001; Emanuel, 2005; Webster et al., 2005; Anthes et al., 2006; Hoyos et al., 2006; Mann and Emanuel, 2006; Trenberth and Shea, 2006; Chang and Guo, 2007; Holland and Webster, 2007; Kossin et al., 2007; Landsea, 2007; Mann et al., 2007; Elsner et al., 2008; Chen et al., 2009). Moreover, the brief observational record is inadequate for characterizing natural variability in hurricane activity occurring on longer than multi-decadal timescales.

In an effort to extend the hurricane record further into the past, a number of paleohurricane proxies are being developed. These proxies can be categorized into two main types: isotope-based proxies that rely on the detection of tropical cyclone rainfall signatures preserved in corals (Cohen, 2001; Hetzinger et al., 2008), tree rings (Miller et al., 2006), and speleothems (Frappier et al., 2007; Nott et al., 2007), and sediment-based proxies such as cyclone surge-constructed beach ridges (Nott and Hayne, 2001; Nott et al., 2009) and overwash deposits preserved in back barrier lagoons (Donnelly, 2005; Donnelly and Woodruff, 2007; Woodruff et al., 2008a,b; Wallace and Anderson, 2010), coastal lakes (Liu and Fearn, 1993, 2000, 2002; Lambert et al., 2003, 2008), and marshes (Donnelly et al., 2001a,b, 2004; Scileppi and

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Donnelly, 2007; Boldt et al., 2010). Isotope-based proxies have in some cases provided exceptional, sub-annual resolution; however, such records often span only a relatively short interval of time. While sediment-based proxies have yielded much longer records reaching back several millennia, low sediment accumulation rates and high flooding thresholds at most sites studied have resulted in low resolution records of high magnitude events. For these reasons, paleohurricane frequency in existing sediment records has usually averaged less than one storm per century. Such low probabilities of occurrence make it difficult to differentiate significant changes in storm climate affecting a site from the random, temporal clustering of events that could result merely from the stochastic nature of hurricane landfalls at any particular location.

In this study, we develop a 4500-year record of hurricane storm surges impacting Bald Point, Florida. The record, developed from the sedimentary archive preserved in a coastal sinkhole, provides sub-decadal resolution and is the first produced from this type of depositional environment. The average event frequency of 3.9 storms per century, greater than that of any published paleohurricane record, permitted the objective identification of intervals with significantly elevated storm frequency as well as abnormally inactive periods in the Northeastern Gulf of Mexico during the last half of the Holocene.

1.2. Study area

Apalachee Bay, situated in the Big Bend region of Florida's Gulf Coast, encompasses 400 km^2 of the coastal shelf submerged to an average depth of 3 m (USEPA, 1999) (Fig. 1a,b). This shallow, concave bay is highly susceptible to extreme storm surges generated by hurricanes that frequent the Gulf of Mexico. Storm tide frequency analysis by a joint probability method suggests that the expected 100-year still water level surge in the bay is about 4.5 m above mean sea level (Ho and Tracey, 1975). Storm surges in excess of 4 m have been observed in the area (Ludlum, 1963; Case, 1986), and inundation modeling indicates that surges exceeding 8 m, which would penetrate tens of kilometers inland, can occur under plausible storm conditions (Jelesnianski et al., 1992).

Bald Point, a roughly 40-km^2 peninsula adjoining Ochlokonee Bay to the north and Apalachee Bay to the east and south (Fig. 1b), is perforated by dozens of sinkholes. The local landscape rests on hundreds of meters of underlying limestone and dolomite, which is overlain by a veneer of clastic sand and clays that, in turn, is covered by a layer of fine quartz sand ten to sixty meters thick (Puri and Vernon, 1964; Sinclair and Stewart, 1985). The pH of meteoric water is lowered by its contact with the atmosphere and organics in the soil, and the acidity of the resulting

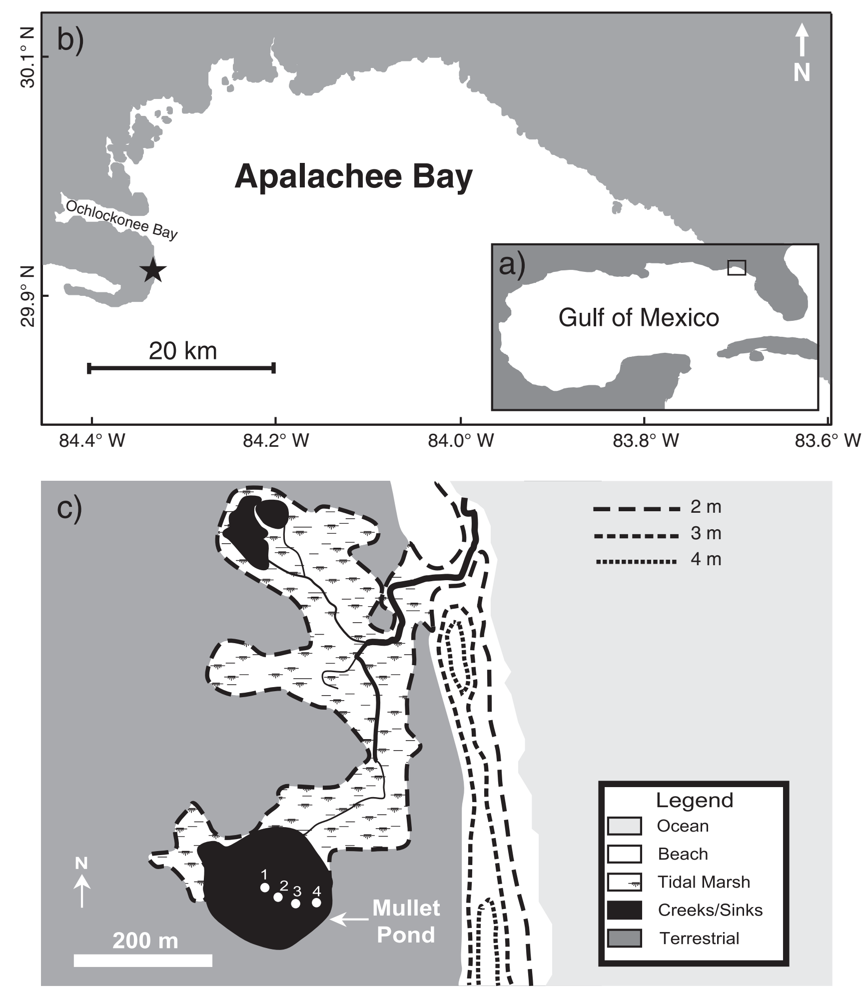

Fig. 1. Regional and local site maps. Panel (a) shows the Gulf of Mexico with the location of Apalachee Bay indicated by the black rectangle. Panel (b) is a regional map of Apalachee Bay showing the Bald Point peninsula near 29.9° N and 84.4° W, and the location of Mullet Pond is indicated by the black star. Panel (c) is a local site map showing that Mullet Pond is situated approximately 350 m to the west of the Bay at the southernmost extent of a salt marsh. Numbered core locations are shown as white circles. Mullet Pond is connected to the Bay by the tidal creek to the north but is otherwise separated from the ocean by a 3–4 m beach dune ridge 200 m to the east. Topography between 2 and 4 m (NAVD88) is contoured at 1 m intervals. The marsh surface and seaward portions of the beach have elevations of less than 2 m. The highest elevations (3 to 4 m) exist along the dune ridge axis on the western portion of the beach, though the ridge adjacent to the pond and southern portion of the marsh is slightly less elevated. Most of the landscape is nearly flat with an elevation between 2 and 3 m.