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Intense Southwest Florida hurricane landfalls over the past 1000 years

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ABSTRACT

Recent research has proposed that human-induced sea surface temperature (SST) warming has led to an increase in the intensity of hurricanes over the past 30 years. However, this notion has been challenged on the basis that the instrumental record is too short and unreliable to reveal long-term trends in hurricane activity. This study addresses this limitation by investigating hurricane-induced overwash deposits (paleotempestites) behind a barrier island in Naples, FL, USA. Paleotempestologic proxies including grain size, percent calcium carbonate, and fossil shells species were used to distinguish overwash events in two sediment cores spanning the last one thousand years. Two prominent paleotempestites were observed in the top 20 cm of both cores: the first identified as Hurricane Donna in 1960 whereas an older paleotempestite (1900–1930) could represent one of three documented storms in the early 1900s. An active period of hurricane overwash from 1000 to 500 yrs. BP and an inactive period from 500 to 150 yrs. BP correlate with reconstructed SSTs from the Main Development Region (MDR) of the North Atlantic Ocean. We observe an increased number of paleotempestites when MDR SSTs are warmer, coinciding with the Medieval Warm Period, and very few paleotempestites when MDR SSTs are cooler, coinciding with the Little Ice Age. Results from this initial Southwest Florida study indicate that MDR SSTs have been a key long-term climate driver of intense Southwest Florida hurricane strikes.

1. Introduction

Understanding fluctuations in hurricane activity has become critically important given the continued population expansion of coastal areas. Due to their powerful winds, high waves, torrential rains and storm surge causing flooding, hurricanes are the single most costly and destructive weather disaster in the United States (U.S.) (Emanuel, 2005). Hurricane damages in the U.S. alone are estimated at $9 billion every year (mean value for 1950–2008) (Nordhaus, 2010). Recent work by Mendelsohn and Saher (2011) suggests that income and population growth are expected to increase the baseline damage from $9 to $27 billion per year by 2100. Furthermore they note that climate change is expected to increase damage by another $40 billion, with over 85 percent of these impacts expected in Florida and the Gulf Coast region. Florida is particularly vulnerable to hurricanes because it is a peninsula with subtropical warm water on three sides. Typically, hurricanes developing in the Main Development Region (MDR: 10° N to 20° N and 20° W to 60° W) of the North Atlantic (Goldenberg and Shapiro, 1996; Saunders and Harris, 1997) move in a general westward direction across the North Atlantic Ocean, making landfall on Caribbean Sea islands and landmasses along the Gulf of Mexico and Southeastern U.S. seaboard. On average, a hurricane threatens to impact portions of the state of Florida every two years (Malmstadt et al., 2009). This problem is exacerbated by a rapidly increasing population and a densely populated coastline. Most of Florida's coastline is less than 2.5 m above sea level and at high risk of inundation by rising sea levels (Stockdon et al., 2012).

Several lines of evidence suggest that anthropogenic climate change may substantially influence hurricane activity worldwide. When considering thermodynamic changes alone, research indicates that global hurricane frequency should diminish, but the incidence of high-intensity events will increase (Emanuel et al., 2008). The percentage of high-intensity storms is indeed increasing (Webster et al., 2005; Elsner et al., 2008). In the North Atlantic basin, where records of directly observed hurricanes are longer and generally of better quality, hurricane frequency and intensity correlate strongly with SSTs where storms typically develop (Emanuel, 2005, 2007; Elsner, 2006; Holland and Webster,

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2007; Saunders and Lea, 2008).

In addition to SSTs, the El Niño-Southern Oscillation (ENSO) influences the formation and pathway of hurricanes (e.g. Bove et al., 1998). ENSO changes have far-reaching impacts, directly affecting global hurricane activity via SST, vertical wind shear, mid-tropospheric relative humidity, low-level relative vorticity, and other factors (Gray, 1984; Gray and Sheaffer, 1991; Goldenberg and Shapiro, 1996; Knaff, 1997; Collins and Mason, 2000). The impact of El Niño and La Niña on hurricane variability in the North Atlantic basin has been studied widely, with storm frequencies, durations, and intensities generally decreasing when El Niño conditions are present (Landsea et al., 1999) and increasing when La Niña conditions occur (Xie et al., 2005; Lupo et al., 2008). Furthermore, the favored genesis regions and storm tracks are impacted (Elsner and Kara, 1999) with decreased activity in the MDR during El Niño conditions. This in turn leads to changing landfall patterns along the U.S. and Caribbean coastlines, with risk of more frequent and stronger strikes during La Niña conditions, less frequent and weaker strikes during El Niño events (O'Brien et al., 1996; Pielke and Landsea, 1999; Tartaglione et al., 2003; Smith et al., 2007), and moderate risk noted during ENSO neutral conditions (Bove et al., 1998). For this reason, ENSO is used as a critical predictor in empirical forecasting of hurricane frequency in a given year.

Though prior work highlights the importance of understanding hurricane dynamics, our understanding of the processes that control the formation, intensity, and track of hurricanes is still restricted (Goldenberg et al., 2001). Most limiting is the 161-year old North Atlantic Basin hurricane record (Landsea et al., 2013), a record too short to reveal long-term trends in hurricane activity (centuries to millennia). This limitation can be overcome using paleotempestology, a relatively new field that identifies past hurricane activity through use of geological (e.g. Liu and Fearn, 2000) and biological (Elsner, 2007) proxies. Most paleotempestological records are created using preserved hurricane overwash signatures. In these studies, the combination of storm surge and waves overtopping barrier beaches produces overwash signatures in back-barrier environments (Schwartz, 1975; Donnelly et al., 2001). Some of the best sites for preserving overwash deposits, and thus archives of hurricane landfalls, are coastal lakes, lagoons, and marshes (Liu and Fearn, 1993; Hippensteel and Martin, 1999; Liu and Fearn, 2000; Donnelly et al., 2001, 2004). The sediment and microfossils from these locations have been used to document prehistoric storm frequency and recurrence intervals (Hippensteel and Martin, 1999; Donnelly et al., 2001; Scott et al., 2003; McCloskey and Keller, 2009; Lane et al., 2011).

Paleotempestological analyses have been undertaken along the northern U.S. Gulf Coast (e.g. Liu and Fearn, 1993, 2000; Lane et al., 2011) and along the North Atlantic coast from South Carolina (e.g. Hippensteel and Martin, 1999; Scott et al., 2003) to New Jersey and New England (e.g. Donnelly et al., 2001, 2004). In addition, records from Belize (McCloskey and Keller, 2009; Denommee et al., 2014), Puerto Rico (Donnelly and Woodruff, 2007; Woodruff et al., 2008) and the Bahamas (Park, 2012) exist. These studies indicate that the frequency of hurricane landfalls in these regions has varied on centennial to millennial scales and that the position of the polar jet stream and the Bermuda-Azores High, variations in ENSO and the African Monsoon, and SSTs likely have long-term effects on hurricane landfalls. More recently, the assembly of paleotempestological research from multiple North Atlantic basin sites affirms an ENSO link and a connection to tropical North Atlantic warmth (Mann et al., 2009).

These pioneering studies have yielded important information on long-term hurricane dynamics. However, the records are confined to a few geographical locations. To date, no well-established paleo-hurricane records exist for the densely populated Southwest Florida coast, even though this area is a prominent hurricane target zone with a return period of 7–8 years for hurricane-strength storms (Neumann, 1991). To address this issue, we use the paleotempestology proxies of grain size, percent $CaCO_3$, and shell species from Southwest Florida lagoonal sediment cores to reconstruct 1000 years of hurricane history.

2. Material and methods

2.1. Site description and field work

Our study site, Island Bay, is located behind Keewaydin Island in Southwest Florida (Fig. 1). Keewaydin Island, located northwest of the Ten Thousand Islands and Everglades National Park, is one of many barrier islands that extend along Florida's west coast (Yale, 1997) and forms the outermost barrier of the Rookery Bay National Estuarine Research Reserve. The age of this barrier island is unknown, though the southern end of the island has a complex history dating back at least 3000 years (Barthle and Savarese, 2009), and other barrier islands in the area have been dated to approximately 2700 yrs. BP. (Savarese et al., 2004; Wohlpart et al., 2007). Island Bay is one of the many tidally influenced, brackish back-barrier lagoons protected by Keewaydin Island. The lagoon is connected to the eastern inner-coastal waterway via narrow mangrove-lined tidal channels, which transport very fine-to fine-grained sands and silts (<250 μm). Storm surge into the lagoon via these channels is not likely to occur given the protective nature of the site and low tidal regime. In this calm, protected region behind the barrier, organic rich, soft-sand bottoms are dominant, with occasional oyster beds (*Crassostrea virginica*) that occur marginally. However, little evidence of prolific oyster reefs exist in Island Bay. In addition, very limited bivalve, gastropod, mollusk, and crustacean growth exist within the lagoon.

Two coring locations within Island Bay were marked by GPS (Fig. 1). Cores were taken at these locations by hand-coring technique, using an aluminum pipe of three-inch diameter and detachable handles. To account for sediment compaction, the height of the sediment outside the pipe was subtracted from that on the inside of the pipe. The sediment core was then extracted by filling the remainder of the pipe with water and then sealing the pipe to create a vacuum. Extra pipe was cut from the top of the core and the core was re-capped before transportation. Cores were taken back to the Florida Gulf Coast University (FGCU) sedimentary laboratory and split for analysis. Using a Trimble RTK unit, model 8A, a beach profile was obtained seaward of the bay across the barrier island to determine the relative vulnerability of the site to storm overwash (Fig. 2). The elevation of the core sediment surfaces relative to mean high water was also obtained and calibrated against NAVD88 using a surveyed landmark.

2.2. Radiometric dating

Our sediment core chronology relies on both ^{210}Pb and ^{14}C radiometric dating techniques. Bulk samples were taken at intervals ranging from 1 to 7 cm in the uppermost 25 cm of core 1206-22 (Table 1). These sediments were analyzed for ^{210}Pb activity using a GAM-AN1F Germanium Detector. The ^{210}Pb age model is based on a constant rate of supply (CRS) model (Binford, 1990).

For the remainder of core 1206-22, available plant and wood fragments were collected, cleaned, dried, and sent to Beta Analytic, Miami, for radiocarbon dating. Three radiocarbon dates were obtained for core 1206-22 and one for core 1206-23 (Table 1). Calibration curves from the Calib7 program with IntCal13 and MARINE13 datasets were used to calculate ^{14}C calendar ages (in years before present, where present is 1950 A.D. by convention) and corresponding uncertainties (Reimer et al., 2013).