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Notes

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Abstract: Hurricanes annually threaten the Atlantic Ocean margins. Historical hurricane records are relatively short and palaeohurricane sedimentary archives provide a geological and climatic context that sheds light on future hurricane activity. Here we review palaeo-trends in hurricane activity elucidated from sedimentary archives. We discuss dating methods, site selection and statistics associated with previously published records. These archives have been useful for understanding the long-term evolution of coastal systems and the response of intense hurricane activity to climatic changes. Regional shifts in hurricane overwash on centennial to millennial timescales have been linked to various climatic modes of variability, including El Niño/Southern Oscillation and the North Atlantic Oscillation, but could also reflect regional-scale controls on hurricane activity.

Growing human populations along the Gulf of Mexico, Caribbean and western North Atlantic coastlines of the USA are annually threatened by hurricanes. The roughly $180 billion combined estimated US damage alone caused by hurricanes Katrina (2005), Ike (2008) and Sandy (2012) serves as a stark reminder of their impact (Knabb *et al.* 2005; Berg 2009; NOAA 2013*a*). In addition to their devastating socioeconomic effects, hurricanes cause environmental, geomorphodynamical, hydrological and ecological perturbations (Boose *et al.* 1994; Myers & van Lear 1998; Pielke & Landsea 1998; Greening *et al.* 2006; Donnelly & Giosan 2008; Philpott *et al.* 2008). Long-term palaeotempestological records are important to assess risk associated with these various hurricane-induced environmental impacts. Landfall rates vary regionally, so it is important to have reconstructions from a number of locations to assess the spatial variability of hurricane impacts. Traditionally, this has been done through an analysis of the historic record. However, palaeotempestological records are providing a new and valuable perspective on the longer-term relationship between climate change and hurricane activity. North Atlantic hurricane activity has been linked to the modern increasing sea-surface temperatures (SSTs) (Emanuel 2005), with an increase in frequency (Webster *et al.* 2005) and magnitude of the strongest events (Elsner *et al.* 2008*a*). Simulations also show regional variability and uncertainties of hurricane activity associated with different model predictions (Emanuel *et al.* 2008).

Within the hurricane modelling and projection community, there appears to be some consensus that the strength of the highest magnitude events will increase owing to future global change, coupled with an overall decrease in the total frequency of events (Knutson *et al.* 2010). However, the historic records that are relied upon to support these conclusions are relatively short and thus make it difficult to identify and interpret trends that may be operating over longer timescales (centuries to millennia). Furthermore, climate conditions present over the instrumental record are not necessarily an accurate representation of climate in the oncoming century. Event deposits preserved within coastal sediments extend hurricane records beyond the historic timeframe to intervals of significantly different climatic conditions. In doing so, geological

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archives provide a means for exploring a non-analogue parameter space in order to gain insight into the response of tropical cyclone activity to varying environmental conditions. Here we provide a review of palaeotempestological research in the Gulf of Mexico, Caribbean Sea and western North Atlantic Ocean margins. We begin with a brief summary of the state of knowledge for modern hurricane climatology as well as the main regions impacted by these storms. We then summarize the various storm proxies, which have been observed within natural archives, followed by a more detailed discussion of methods and results obtained by sedimentary reconstructions of hurricane occurrences from these regions.

Modern hurricane climatology

The hurricane genesis and impact region of the Atlantic includes the Northern Atlantic, Gulf of Mexico and Caribbean Sea. Hurricanes generally form (Gray 1998) under a given set of criteria (NOAA 2013*b*): (a) warm ocean waters of at least *c.* 27 °C within the water column to a water depth of about 50 m; (b) rapidly, high cooling atmosphere; (c) mid-troposphere-level moist air; (d) generally at least 500 km away from the equator; (e) an initial near-surface atmospheric disturbance (such as easterly waves, tropical upper-tropospheric trough, old frontal boundary); and (f) low vertical wind shear. Owing to these factors, major hurricanes are typically constrained to latitudes between about 5 and 40°N.

Atlantic tropical storms can be clustered by their genesis and landfall location, with Kossin *et al.* (2010) presenting four separate clusters for the North Atlantic. In general, storms in clusters 1 and 2 form further to the north than clusters 3 and 4 (Fig. 1). Roughly 33, 25, 29 and 13% of tropical storms and hurricanes occur within clusters 1, 2, 3 and 4, respectively. Cluster 2 storms are generated in the Gulf of Mexico and Caribbean, whereas Cape Verde storms (originating from atmospheric waves and disturbances derived from Africa) are represented primarily by clusters 3 and 4. Approximately 55% of tropical storms in cluster 1 grow to hurricane intensity (peak wind speeds equal to or greater than 33 m s^{-1} or 64 knots), compared with 46, 68 and 65% for clusters 2, 3 and 4, respectively.

In addition to the clusters described above, hurricanes can be grouped by the three major coastal regions that they impact (Gulf of Mexico, Caribbean Sea and western North Atlantic Ocean). Hurricanes in the Gulf of Mexico are a common occurrence, owing to relatively warm SSTs and latitudes between about 20 to 30°N (Fig. 1). Loop current divergence of the North Atlantic Gulf Stream occurs through the Caribbean Sea and is characterized by warm water rotating clockwise through the Gulf of Mexico. Hurricanes can

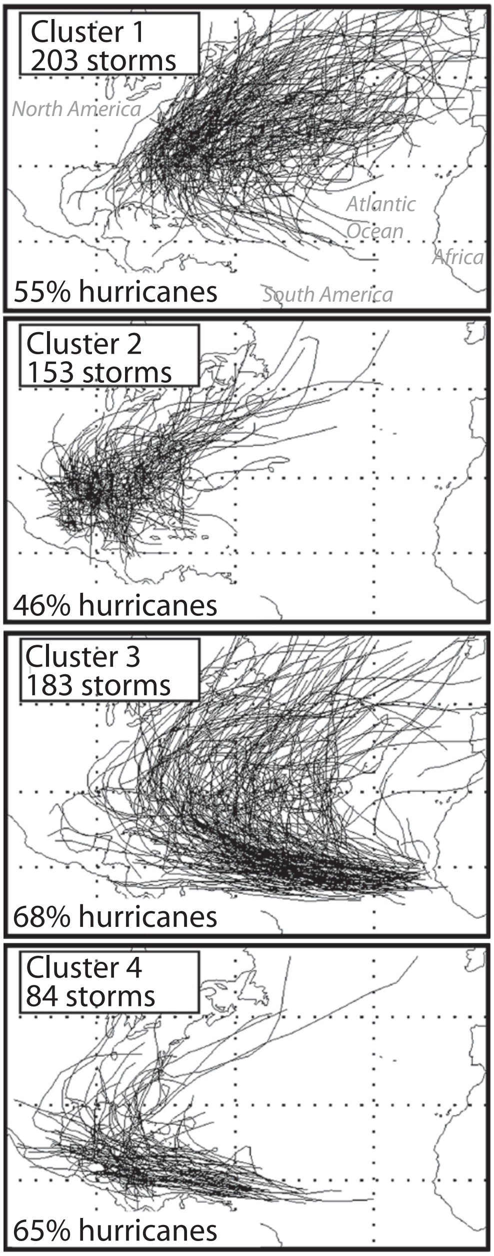

Fig. 1. Four clusters of North Atlantic hurricane tracks for storms from 1950 to 2007 C.E. (modified from Kossin *et al.* 2010). Storms in clusters 1 and 2 form at higher latitudes than clusters 3 and 4. Total storm counts and percentage of the total growing to hurricanes are given for each cluster.

intensify significantly when propagating over this loop current (Shay *et al.* 2000; Scharroo *et al.* 2005) owing to a deeper mixed layer relative to ambient Gulf waters. Although not necessarily unique to the Gulf of Mexico, trapped waves can also amplify storm surges (Morey *et al.* 2006).

The western North Atlantic margin has cooler SSTs at higher latitudes (about 35 to 45°N), primarily resulting in less frequent hurricane activity (Fig. 1). Many of the hurricanes impacting this region originate from atmospheric disturbances shed from West Africa (Cape Verde storms) that recurve to the north as they propagate across the Atlantic, with the strength and frequency of these events generally declining as SSTs drop at latitudes above *c.* 35°N (Fig. 1). Many of these systems transition to extratropical storms as they propagate further northward, and landfalls of extratropical systems along this region occur at a rate of about one to two storms per year (Hart & Evans 2001). Hurricanes are also a common occurrence throughout the Caribbean, owing to relatively warm SSTs and latitudes between about 10 and 20°N (Fig. 1). This region is also impacted by more Cape Verde storms (Fig. 1) that can continue on to the Gulf or recurve to the north, causing later impacts along the eastern seaboard of the USA.

Simulations for the coming century are often regionally variable, and highlight the uncertainties associated with future hurricane activity (Emanuel *et al.* 2008). For example, the CNRM-CM3 (Centre National de Recherches Météorologiques, Météo-France), CSIRO-Mk3.0 (Australian Commonwealth Scientific and Research Organization) and ECHAM5 (Max Planck Institution) models all suggest an increase in the western Atlantic hurricane genesis density in the coming century, with little change or a possible decrease in genesis density in the Gulf of Mexico and Caribbean Sea (Emanuel *et al.* 2008). However, another simulation (GFDL-CM2.0: NOAA Geophysical Fluid Dynamics Laboratory) suggests an increase in genesis density for the entire western Atlantic Ocean basin for the coming century (Emanuel *et al.* 2008). Recently, historic and future climate was simulated using six Coupled Model Intercomparison Project 5 (CMIP5) global climate models and also showed increased tropical cyclone activity for the twenty-first century (Emanuel 2013).

Coastal geology

Hurricane impacts can have a profound affect on the evolution of coastal systems (Fig. 2), including offshore environments, sandy barrier islands, beaches and strandplains. The eroded sands are transported offshore and alongshore through backwash, nearshore currents and littoral drift, and onshore through overwash. This can drive the evolution of coastal systems (Morton 2002; Morton & Sallenger 2003; Stone *et al.* 2004; FitzGerald *et al.* 2008; Houser *et al.* 2008), with variations in sediment supply from other processes (fluvial, transgressive ravinement) providing an additional governor of change. Further inland, extreme precipitation can induce severe freshwater flooding, as well as mass wasting events such as landslides. All of these factors can vary between storms and depend on the specific local geology of the coastal system being impacted.

Holocene sediments along the northern Gulf of Mexico (Fig. 3) margin are mostly siliciclastic, although there are carbonates in the east (Florida; USGS 2013*a*). In general, gentle offshore slopes characterize the margins along the northern Gulf of Mexico, with shelf widths ranging from about 30 to 180 km. The onshore coastal plains consist of large rivers and deltas, including the Mississippi River, in general leading to relatively high sediment supply in the region, although currently anthropogenic modifications are having a significant impact in some locales. Sandy barrier islands, strandplains and bay/estuary systems are also abundant along the Gulf of Mexico (USGS 2013*a*).

The western North Atlantic margin (Fig. 3) comprises siliciclastic sediments in the north, while the southern section is composed of siliciclastic and carbonate sediments (Florida; USGS 2013*a*). In general, the western North Atlantic margins are characterized by relatively gradual offshore gradients (shelf widths ranging from about 50 to 300 km), with these gradients becoming even gentler towards the south (shelf widths of about 400 km). Tidally influenced rivers, estuaries and small deltas also characterize the western North Atlantic coastal plains, along with sandy barrier islands, strandplains and bay/estuary systems (USGS 2013*a*). Unique landscapes conditioned in part by the Last Glacial Maximum are also present along the western North Atlantic margin and include large glacial moraines (such as Long Island, New York and Cape Cod, Massachusetts), kettle lakes and drumlins (Colgan *et al.* 2003).

The Caribbean Sea (Fig. 3) represents the only active tectonic setting in the northwestern Atlantic, and it is encircled with volcanic island arcs capped by carbonates that typically define the north and eastern edge of the Caribbean Plate (USGS 2013*b*). The volcanic Caribbean margins are characterized by steep onshore and offshore gradients and lack the prominent coastal plains found along the Gulf of Mexico or Atlantic margins (USGS 2013*b*), although extensive regions of shallow nearshore and offshore bathymetry exist along carbonate platforms in locations like the Great Bahama Bank (Fig. 3).

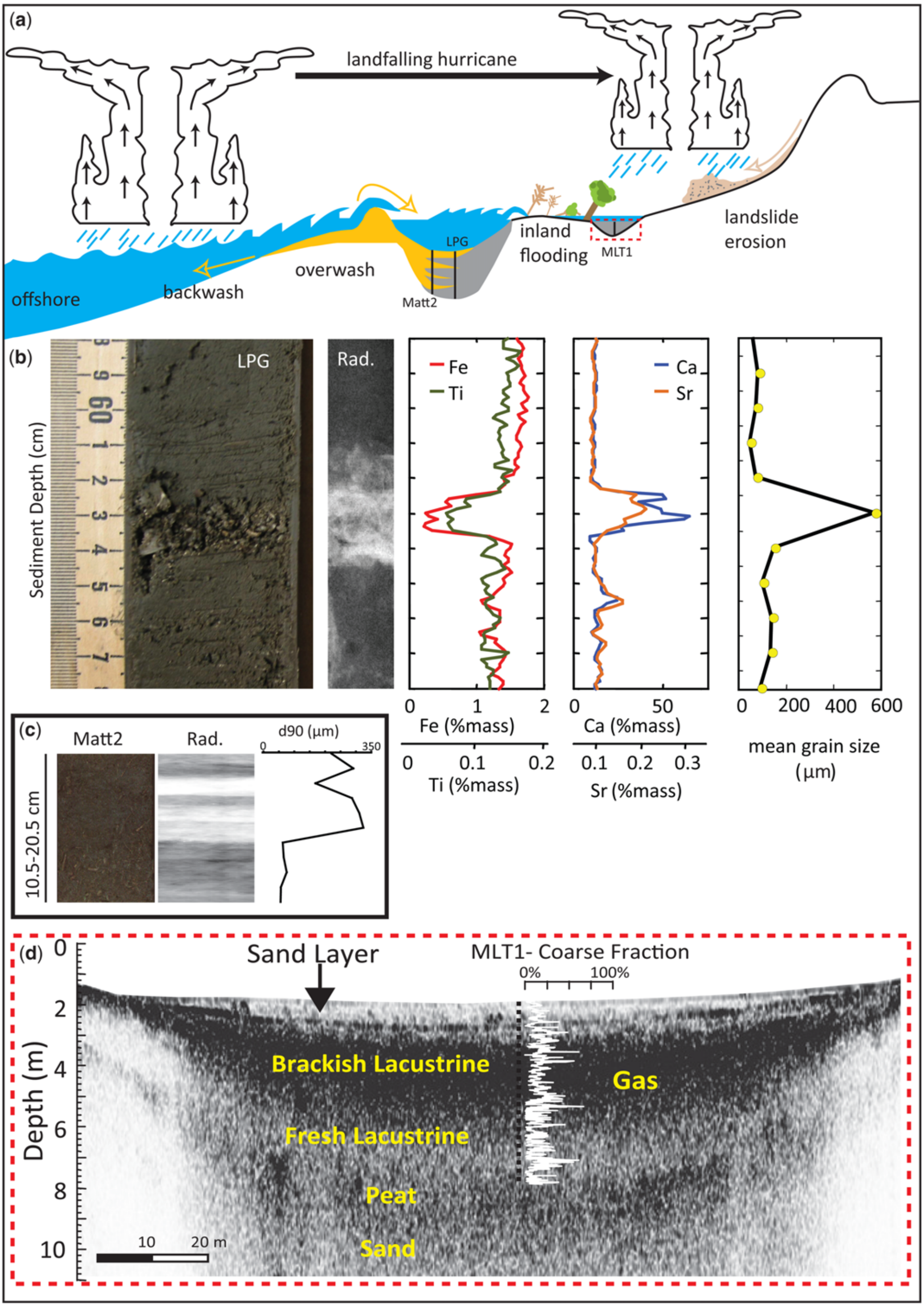

Fig. 2. (**a**) Schematic diagram depicting a landfalling hurricane and their impacts on offshore, nearshore and inland environments (modified from Liu 2004). LPG, Matt2 and MLT1 identify environments where sediments in b, c, and d were collected, respectively. (b–d) Representative environments and methods for identifying palaeohurricane events.

Hurricane proxies from natural archives

Kenneth O. Emery was probably the first to reconstruct late Holocene hurricane deposits. In his investigation of Oyster Pond, Massachusetts (Cape Cod), he identified nine sand layers intercalated with organic deposits, interpreting the former as material transported by hurricanes over the past *c.* 1250 years B.P. (Emery 1969). Today, palaeotempestology utilizes the geological and biological record to reconstruct tropical cyclones impacting locales dispersed throughout most regions of tropical cyclone activity and over a variety of timescales. These records have relied on a number of proxies. Negative ^{18}O anomalies, indicative of hurricane-associated precipitation, can be preserved in tree rings (Georgia, Miller *et al.* 2006) and speleothems (Belize, Frappier *et al.* 2007*a*; Bermuda, Malmquist 1997; Australia, Nott *et al.* 2007). ^{18}O oscillations have also been used to associate boulder deposits with typhoon events (Suzuki *et al.* 2008). Luminescence intensity data from corals have been used as a proxy for hurricane activity in the Caribbean (Nyberg *et al.* 2007) and freshwater flood plumes in Australia are often associated with greater cyclone activity (Lough 2007). The frequency of storm-related floods has also been reconstructed from large riverine floods probably associated with typhoons transporting coarse material in Japan (Grossman 2001). Sand to very coarse material, up to boulder size, transported by cyclones has also been documented in Bonaire (Scheffers & Scheffers 2006), the Lesser Antilles (Spiske *et al.* 2008), Japan (Suzuki *et al.* 2008; Woodruff *et al.* 2009), the South China Sea (Yu *et al.* 2009), Australia (Zhao *et al.* 2009) and French Polynesia (Toomey *et al.* 2013*a*). Coastal geomorphic proxies have also yielded evidence of past tropical cyclone deposits, including beach ridges (Australia, Brooke *et al.* 2008; Nott & Hayne 2001; Nott *et al.* 2009; Nott 2011; Louisiana, Williams 2013) and scarps in the Gulf of Maine (Buynevich *et al.* 2007). Marine foraminifera transported and deposited in non-marine inland settings have also been used as a successful proxy of past tropical cyclone events (Hippensteel & Martin 1999; Scott *et al.* 2003; Williams 2009, 2010) as well as shell-bed tempestites (Scott *et al.* 2003; Williams 2011). The coarse sediment fraction on the inner shelf can also be used to reconstruct hurricane events (Keen *et al.* 2012).

All of the aforementioned proxies potentially record different yet important aspects and characteristics of hurricane deposits. Modern overwash deposits from hurricanes have also been studied extensively (Hayes 1967; Nummedal *et al.* 1980; Kahn & Roberts 1982; Stone & Wang 1999; Sallenger *et al.* 2006; Morton *et al.* 2007; Woodruff *et al.* 2008*a*, *b*; Hawkes & Horton 2012). These modern analogues have improved the interpretation of longer-term reconstructions. To date, coastal sedimentary archives relying on preserved coarse-grained deposits formed during coastal flooding have in general provided the most extensive, directly comparable records of hurricane strikes for different regions of the western North Atlantic. This proxy works under the premise that, during hurricane landfalls, coarse-grained sediments are transported from seaward locales and deposited in coastal systems where the background sedimentation consists primarily of finer-grained and often more organic sediments (Fig. 2). This has typically led researchers to target coastal marshes, ponds, lagoons, bays and estuaries sheltered behind or adjacent to sandy coastlines (such as barrier islands, strandplains and associated shoreface deposits). Sediment records collected in these environments often show coarse-grained layers interbedded with finer-grained, organic-rich autochthonous sediments, where the sand is interpreted to be hurricane-induced event beds. To better understand the dynamics of transport and improve sedimentary interpretations, researchers have ideally selected coastal systems that contain preserved deposits from both modern and pre-historic hurricanes.

Palaeotempestological overwash reconstructions of intense hurricanes have been collected from a number of locales around the Gulf of Mexico (Liu & Fearn 1993, 2000*a*, *b*; Wallace &

Fig. 2. (*Continued*) (**b**) Optical image, X-radiograph, X-ray fluorescence and grain-size data from a representative sediment core collected in Laguna Playa Grande, Puerto Rico (see Donnelly & Woodruff 2007; Figs 3 & 4 for location; modified from Woodruff 2009). From 62 to 64 cm, there is a coarse, inorganic layer that is relatively high in marine sourced Ca and Sr, but relatively low in terrigenous Fe and Ti. This type of evidence can support the interpretation that this event-layer resulted from a high-energy coastal flood event that inundated the adjacent coastal barrier (Donnelly & Woodruff 2007). (**c**) Optical image, X-radiograph and d_{90} grain sizes (90th percentile) from Matt2, a sediment core collected in Mattapoisett Marsh, Massachusetts (modified from Boldt *et al.* 2010; Figs 3 & 4 for location). Note, the optical image often does not readily show event deposits, but they are clearly shown in X-radiographs and grain-size analyses. (**d**) A CHIRP sub-bottom profile from Mullet Pond, Florida (Figs 3 & 4) also showing the percentage coarse fraction anomaly from sediment core MLT1 from the same area (modified from Lane *et al.* 2011). For X-radiographs, white represents coarse-grained, dense mostly sandy material (hurricane deposits) and black represents fine-grained, organic-rich fair-weather, backbarrier deposits.

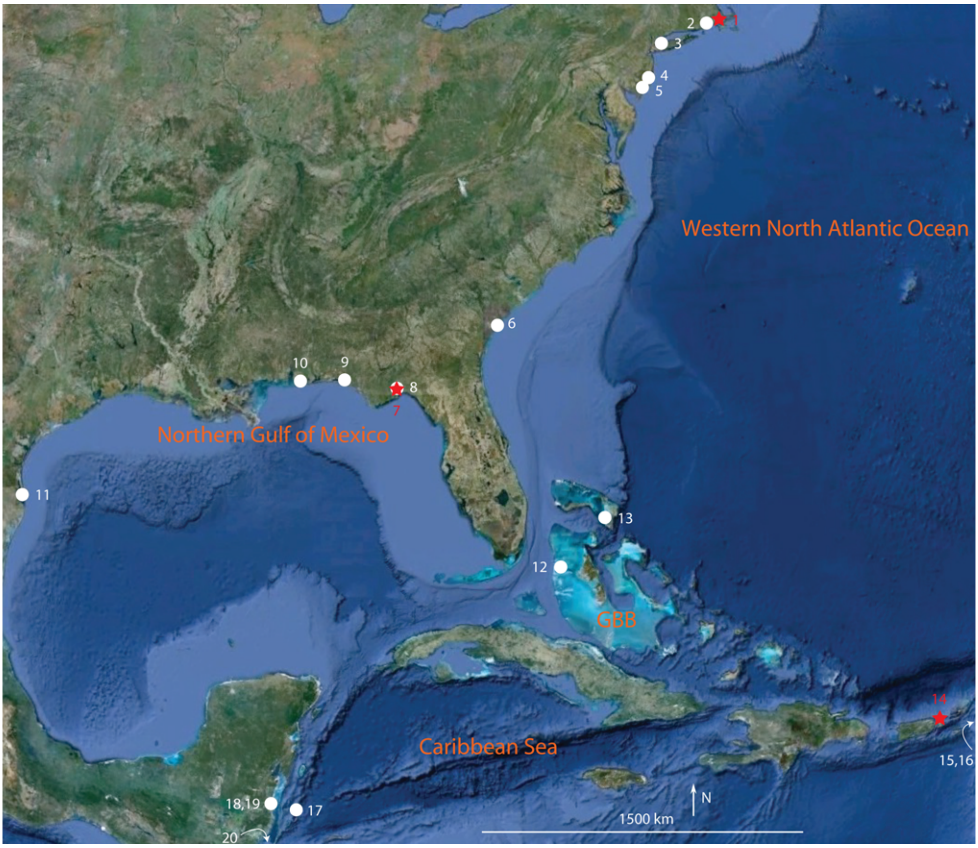

Fig. 3. Location map of palaeohurricane studies documenting intense storms over millennial-scale (white circles) and centennial-scale resolutions (red stars) from the Gulf of Mexico, Caribbean Sea and western North Atlantic Ocean margins (image from Google Earth; data from Scripps Institution of Oceanography, National Oceanic and Atmospheric Administration, United States Navy, National Geospatial-Intelligence Agency, and General Bathymetric Chart of Oceans). 1, Mattapoisett Marsh, Massachusetts (Boldt *et al.* 2010); 2, Succotash Marsh, Rhode Island (Donnelly *et al.* 2001*a*); 3, Alder Island, New York (Scileppi & Donnelly 2007); 4, Brigantine, New Jersey (Donnelly *et al.* 2004); 5, southern New Jersey coast (Donnelly *et al.* 2001*b*); 6, Wassaw Island, Georgia (Kiage *et al.* 2011); 7, Mullet Pond, Florida (Lane *et al.* 2011); 8, Spring Creek Pond, Florida (Brandon *et al.* 2013); 9, Western Lake, Florida (Liu & Fearn 2000*a*); 10, Lake Shelby, Alabama (Liu & Fearn 2000*b*); 11, Laguna Madre, Texas (Wallace & Anderson 2010); 12, western Great Bahama Bank (Toomey *et al.* 2013*b*); 13, Little Bahama Bank (van Hengstum *et al.* 2013); 14, Laguna Playa Grande, Puerto Rico (Donnelly & Woodruff 2007); 15, 16, Saint-Martin (Bertran *et al.* 2004; Malaizé *et al.* 2011) located just off of the map to the east; 17, Blue Hole, Belize (Gischler *et al.* 2008); 18, Gales Point, Belize (McCloskey & Keller 2009); 19, coastal Belize (McCloskey & Liu 2013); 20, Nicaraguan coast (McCloskey & Liu 2012) located just off of the map to the south. GBB, Great Bahama Bank.

Anderson 2010; Lane *et al.* 2011; Brandon *et al.* 2013), Caribbean (Bertran *et al.* 2004; Donnelly 2005; Donnelly & Woodruff 2007; Gischler *et al.* 2008; Woodruff *et al.* 2008*b*; McCloskey & Keller 2009; Malaizé *et al.* 2011; McCloskey & Liu 2012, 2013; Toomey *et al.* 2013*b*; van Hengstum *et al.* 2013) and western North Atlantic Ocean margins (Donnelly *et al.* 2001*a*, *b* 2004; Donnelly & Webb 2004; Scileppi & Donnelly 2007; Boldt *et al.* 2010; Kiage *et al.* 2011; Fig. 3). Here, these reconstructions and their implications are reviewed.

Methods of sedimentary palaeotempestology

Site selection

Identifying the source of coarse-grained material and the process by which it is transported and deposited into a coastal depocentre is important to an accurate interpretation of event stratigraphy (Otvos 2011). This can often be accomplished through observations or documentation of sediment transport associated with storms occurring during historic time. These modern analogues can often aide greatly in the interpretation of prehistoric storms. Additional mechanisms exist for the deposition of coarse-grained layers (such as riverine floods, aeolian processes, sediment winnowing, tidal processes), and these processes should always be considered when developing an accurate interpretation for the event stratigraphy preserved at a particular site (Otvos 1999, 2002, 2009; Hippensteel 2008, 2011; Plant *et al.* 2010). In the western North Atlantic, it is also important to select sites that are oriented such that winter storms have only a minor impact (Boldt *et al.* 2010).

Large-scale tsumani events are rare to the northern Caribbean relative to hurricane occurrences. Nonetheless, some consideration should be taken towards selecting sites that minimize tsunami influence (Donnelly 2005), especially in areas where they are more frequent. Most studies are currently unable to unequivocally delineate between event deposits formed from tsunamis and those from storms (Atwater *et al.* 2012). However, the high frequency of both hurricane occurrences and overwash layers observed at many locations in the western North Atlantic, along with the correlation of recent overwash layers to documented intense hurricane strikes, strongly suggests that a large majority of the overwash layers observed at these sites are the result of intense hurricane activity rather than tsunami events.

A lack of bioturbation is also an important control on the preservation of a storm-related record. The more biologically active a site is, the higher the potential is that a storm record will be obscured or unrecognizable (Martin 1993, 2000; Bentley *et al.* 2006; Hippensteel 2011). For example, it is not uncommon for organisms to immediately start burrowing a washover deposit after a storm, leading to recognizable bioturbation in the sedimentary record. However, if a bed is particularly thin (centimetre scale), the coarse-grained material could easily be homogenized into interbedded fine-grained sediments. Therefore, sites of low biological activity, such as anoxic or hypersaline environments, often have the highest preservation potential of hurricane overwash occurrences.

A relatively high sedimentation rate is also a key component to preserving a complete palaeohurricane record. Without a moderately high sedimentation rate, coarse hurricane deposits will be amalgamated together, and individual or event clusters will be unrecognizable. However, the risk of this amalgamation is related to both the temporal resolution of the sedimentary record and the frequency of events at a site, such that locations with slow sedimentation rates may still be appropriate for distinguishing individual events if events are sufficiently rare. Furthermore, there are feedbacks to consider between the background sedimentation rate and event deposition. For example, a deposit of sufficient thickness has the potential to slow rates of marsh deposition for years to decades following an event. Finally, the location of sampling relative to the source of coarse material can also impact event resolvability within a sedimentary record. A transect of sediment cores from proximal to distal locations relative to the source of coarse material increases the probability of sampling the ideal location for washover; too proximal locations will yield an amalgamation of coarse material, whereas too distal locations will yield an incomplete record of storm events. Geophysical surveys with sub-bottom sonar (CHIRP; Fig. 2d) or ground penetrating radar profiles can often aid in identifying and correlating local stratigraphy. X-ray fluorescence and X-radiographs have also been used to aide in the identification and interpretation of coarse-grained hurricane event deposits (Fig. 2b, c).

Environments capable of long-term preservation are a vital study site-selection criterion. Coarse event layers not buried by backbarrier background sedimentation shortly after deposition are less likely to be preserved owing to erosion and reworking. For this reason, the preservation potential of subaerial deposits is generally low relative to marsh and subaqueous deposits owing to low background sedimentation and enhanced weathering by the elements. Relatively stable morphology is also a necessary credential for a well-preserved and accurate event reconstruction, as the sensitivity of a coastal pond or marsh to overwash processes is determined primarily by the morphology of the barrier or shoreline that separates it from the sea. Barrier beach and marsh systems are advantageous since geomorphic feedbacks have allowed many of these systems to maintain their elevation relative to local sea-level over the last few millennia. Sea-level rise rates were more rapid (*c.* 5–9 mm a^{-1}) in the middle Holocene, and they have slowed dramatically (to *c.* 0.60 mm a^{-1}) over the past approximately two millennia for the North Atlantic and surrounding basins (Törnqvist *et al.* 2004*a*, *b*, 2006; Milliken *et al.* 2008; Kemp *et al.* 2011). These relatively moderate rates of sea-level change over the last few millennia have resulted in a more stable shoreline and a better-preserved record of hurricane overwash (Woodruff *et al.* 2013*b*).

Dating methods

Developing a well-dated reconstruction of historical overwash events is critical for understanding centennial- to millennial-scale storm records. With a half-life of 22.3 years, ^{210}Pb can effectively date sediments deposited over the past 100–150 years (Faure 1986). ^{137}Cs is an unnaturally occurring by-product of nuclear weapons testing that is often used as a companion to ^{210}Pb. The first detection of ^{137}Cs in sediment marks the 1954 Common Era (C.E.) onset of atmospheric weapons testing, followed by a peak abundance that signifies the 1963 C.E. height of testing immediately preceding the Nuclear Test Ban Treaty (DeLaune *et al.* 1978). Post-bomb spike ^{14}C has also recently been utilized for palaeotempostological chronology after *c.* 1950 C.E. (van Hengstum *et al.* 2013).

In addition to these isotopic analyses, several stratigraphic markers can be used for dating sediment. Abrupt increases in Ti have been shown to be a good proxy for detecting changes in run-off from terrestrial sources (Haug *et al.* 2001), and have been utilized in the Northeastern USA to denote early eighteenth-century increases in fluvial sediment load potentially associated with land clearance (Kirwan *et al.* 2011). This proxy has also been used as an effective chronostratigraphic marker in Puerto Rico (Woodruff *et al.* 2008*b*). Furthermore, the initial rise in heavy metal concentrations in the Northeastern USA has been linked to the late 1800s/early 1900s onset of industrial activity (McCaffrey & Thomson 1980; Bricker-Urso *et al.* 1989; Donnelly *et al.* 2001*a*, *b*; Scileppi & Donnelly 2007; Woodruff *et al.* 2013*a*), followed by a decline in Pb associated with the transition to unleaded gas in the mid-1970s (Varekamp *et al.* 2003, 2005). The presence or absence of several types of pollen associated with European-style land clearance and farming practices in the USA occurs at roughly *c.* 1700 C.E. (Rich 1970; Brugam 1978; Clark & Patterson 1985; Donnelly *et al.* 2001*a*; Scileppi & Donnelly 2007) as well as the rapid and widespread destruction of American chestnut by the introduction of an invasive fungus around 1900 C.E. (Anderson 1974; Donnelly *et al.* 2001*b*; Scileppi & Donnelly 2007).

For long-term records, radiocarbon dating has typically been utilized (Libby *et al.* 1949; Libby 1955). With calibration (Stuiver & Kra 1986), radiometric (^{14}C) dating can yield ages extending back in time to about 55 000 years Before Present (B.P.), where Present refers to 1950 C.E. This technique has been used to date organic material (such as leaves and seeds) and carbonate material (such as shells and corals). A radiocarbon reservoir effect is applied to most marine carbonates, and reflects the utilization of old carbon by the material dated (Ascough *et al.* 2005). Optically stimulated luminescence dating is also a relatively new technique for obtaining Quaternary age constraints of storm-related coastal deposits (Buynevich *et al.* 2007; Nott *et al.* 2009).

Statistics

Not all trends observed within palaeostorm reconstructions necessarily reflect larger-scale changes in tropical cyclone climatology. The sensitivity of a site to overwash events may change over time with changes in barrier width and height (Otvos 2002; Lambert *et al.* 2003). For instance, a rapid and monotonic rise in the number of event layers towards present could potentially be explained by the increase in sensitivity of a site to overwash in response to rising sea-level and landward shoreline translation (barrier transgression; Boldt *et al.* 2010), or to a reduction in barrier elevation by preceding storms. However, a decrease in the number of overwash events towards present is more difficult to explain with this type of biasing. Changes in sedimentation rates, particularly associated with land clearance during historic time, or erosional hiatuses provide additional biases (Woodruff *et al.* 2008*a*; Brandon *et al.* 2013). Furthermore, the stochastic nature of tropical cyclone strikes to a single site provides an additional level of uncertainty when inferring temporal overwash patterns to true changes in hurricane climatology. For example, if climate were to remain constant through time, what types of variability should be expected solely owing to the random nature of hurricane strikes to a single site? As the time period of interest shortens, random variance in landfall rates increases relative to true trends in Atlantic basin hurricane activity. Such stochastic noise makes it challenging to detect any modern changes in hurricane frequency over the most recent century from a single site. Conversely, as the timescale of interest increases, variability associated with random chance decreases and trends observed in hurricane reconstructions begin to reflect larger-scale shifts in tropical cyclone activity.

Recent statistical approaches have begun to quantify the significance of trends within palaeostorm archives (Elsner *et al.* 2008*b*; Woodruff *et al.* 2008*a*; Lane *et al.* 2011; Mann *et al.* 2009). Woodruff *et al.* (2008*a*) combine results from a coupled atmosphere–ocean hurricane model and a newly derived method for generating simulated sedimentary records of hurricane overwash. The model is set to modern climatological conditions, and periods of anomalous hurricane activity are defined as times when observed trends in a prehistoric storm reconstruction fall outside the variance that could be produced under current hurricane climatology. The approach is applied to a palaeohurricane reconstruction from Vieques, Puerto Rico by Donnelly & Woodruff (2007), and shows that centennial-scale breaks in overwash activity are exceptionally long and are unlikely to occur (above 99% confidence) under the current climate. Results from this study therefore supply quantitative evidence for the western North Atlantic experiencing significant changes in hurricane climatology over the last 5000 years.

Lane *et al.* (2011) apply a method similar to Woodruff *et al.* (2008*a*) to construct confidence intervals for the random portion of variability within a 4500 year B.P. sedimentary record of storm frequency from a north Florida sinkhole (Mullet Pond). However, for this application the average storm frequency was prescribed by the sediment record itself rather than by the coupled atmosphere–ocean hurricane model of Emanuel *et al.* (2006). For the Lane *et al.* (2011) analysis, ten-thousand 157-year- long artificial bootstrap (random draw from a dataset with replacement) records were generated. Similar to Woodruff *et al.* (2008*a*), the occurrence of a storm in each bootstrap record was modelled as a Poisson process, but with the average storm frequency equal to that of the whole sedimentary record (rather than a frequency prescribed by modern hurricane climatology). The confidence interval for the random portion of variability within the entire Mullet Pond record was quantified based on the variance within the catalogue of modelled storm frequencies from each bootstrap sample. Results by Lane *et al.* (2011) indicate that in Florida overall hurricane occurrences remained relatively constant over the last few millennia. However, the frequency of larger coarse storm layers (probably associated with major hurricanes) was found to be greater than what would probably be expected from randomness alone, indications that distinct periods of increased intense hurricane activity occurred prior to *c.* 600 years B.P.

Like many palaeohurricane records, the Vieques, Puerto Rico and Mullet Pond, Florida records contained deposits attributable to historical hurricanes of known intensity. These modern analogues provide the opportunity to calibrate a threshold flood intensity required for hurricane-induced overwash at a site. Uncertainty related to this threshold is often large since this analogue method is based on only a few modern events. Complications expand further when no modern events are detected at a site, such as within one of the earliest storm records from the northern Gulf of Mexico at Lake Shelby, Alabama (Liu & Fearn 1993). Elsner *et al.* (2008*b*) applied a peak-over-threshold analysis of the best track dataset to assess the threshold wind speed required to produce the return frequency observed for prehistoric storm deposits within the Lake Shelby record. The peak-over-threshold method assumes constant climatic conditions over the *c.* 3500 year period, which is a potential limitation of the approach. However, Elsner *et al.* (2008*b*) argue that an exponential distribution for the temporal spacing between events could not be statistically rejected, and in turn the assumption of uniformity could not be ruled out based solely on the Lake Shelby reconstruction.

Mann *et al.* (2009) expanded upon these previous assessments of past changes to hurricane activity by compiling records to assess basin-wide shifts in activity. Errors associated with the age model of each sedimentary reconstruction were recognized by deriving an ensemble of possible event chronologies for each sedimentary reconstruction with event ages randomly deviating within $\pm 1\sigma$ limits of radiocarbon age uncertainties. Further uncertainty associated within individual regional reconstructions are constrained by developing separate time series that exclude single reconstructions from the larger basin-wide composite, with the spread in these jackknife surrogates (using data subsets) used to define the standard error in the larger time series composite of basin-wide landfalling hurricane rates. This sedimentary composite is compared with an independent statistical model of Atlantic tropical cyclone activity using proxy information on El Niño/Southern Oscillation (ENSO), SSTs from the tropical Atlantic, and the North Atlantic Oscillation (NAO). In general the two independent estimates for tropical cyclone activity fall within each other's bounds of uncertainty, with both approaches yielding consistent evidence of a peak in Atlantic tropical cyclone activity during medieval times (around 1000 C.E.) followed by a subsequent lull in activity. However, notable discrepancies exist between the separate event-layer and the ENSO/SST/NAO based reconstructions, including a mid-fifteenth-century peak in activity from the sedimentary reconstructions not predicted by the statistical model. Divergences between the two independent reconstructions may provide evidence for: (a) climate forcings other than ENSO, SST and the NAO driving observed variability in landfalling hurricane rates; (b) limitations associated with the basin-wide synthesis approach; (c) more regionally specific drivers such as NAO changes to storm tracks (Elsner *et al.* 2000) or variability in loop current penetration in the Gulf of Mexico (Lane & Donnelly 2012; Brandon *et al.* 2013); or (d) limitations in the quantity and distribution of both storm and palaeoclimate reconstructions.

Limitations exist for all of the various datasets of historic hurricane activity (Landsea *et al.* 2004; Chang & Guo 2007; Mann *et al.* 2007; Chenoweth & Divine 2008; Vecchi & Knutson 2008; Villarini *et al.* 2011), and sedimentary records of hurricane-induced overwash are no exception. The spatial distribution and number of overwash records are still limited, and will never reach the coverage provided by instrumental records. However, what palaeorecords lack in spatial distribution they make up for in time coverage. Furthermore, statistical assessments show that these sedimentary records are well suited to assessing tropical cyclone activity on centennial and millennial timescales and provide a window into past changes occurring prior to the instrumental record. Thus, they provide the only observational means of comparing storm magnitude and frequency to variations in climate and SSTs occurring over these longer timescales.

Sediment transport modelling

Sediment transport modelling has helped understand the mechanisms of palaeohurricane sediment deposition. This work often takes the inverse approach of back-calculating flow conditions during hurricane overwash based on the observed grain-size distribution and thickness of resultant deposition. Much of the initial inverse modelling work on event deposits from coastal flooding has involved tsunami sediment transport; however, more recently similar techniques have been successful in hurricane applications as well.

Jaffe & Gelfenbaum (2007) propose a simple spatially uniform model of vertical settling to back-calculate tsunami flow speed from the thickness of tsunami deposits and corresponding grain-size distributions. The technique relates the thickness and bulk grain size of a deposit to a likely water-column sediment concentration profile, assuming that this profile reflects peak flow conditions and that the deposit is primarily derived from the vertical clearing of this sediment profile from the water column, with minimal bed-load transport. The 1-D model assumes that water is more or less stagnant at the time of clearing and that flow is steady with minimal deposition associated with horizontal convergences in sediment flux.

Moore *et al.* (2007) proposes an alternative inverse model assuming the dominance of lateral/horizontal sorting. Here the timescale of horizontal advection is matched to the time of vertical settling:

$$\frac{h}{w_s} = t = \frac{x_L}{U}, \qquad (1)$$

where h is the water depth at peak flooding, w_s is the maximum particle settling velocity (see Ferguson & Church (2004) for a recent grain size v. w_s derivation) of grains advected landward a distance of x_L from the sediment source, and t is the settling time. The onshore flow is treated as a short-duration unidirectional flow rather than a wave set. Here, U is the depth-averaged turbulent vertical velocity profile ('law of the wall'):

$$U = \frac{u_*}{K}\left(\ln\left(\frac{h}{z_0} - \left(1 - \frac{z_0}{h}\right)\right)\right), \qquad (2)$$

where z_0 is the bed roughness length scale (often $D_{84}/30$ for a rough hydraulic flow; Middleton & Southard 1984), K is von Karman's constant, and u_* is the shear or friction velocity (a function of the fluid density, bottom drag and flow velocity).

Assuming critical flow over the barrier ($U = (gh)^{1/2}$), Woodruff *et al.* (2008*b*) obtains a more simplified advective/settling derivation for flow depth over a barrier $\langle h_b \rangle$:

$$\langle h_b \rangle = \left(\frac{{x_L}^2 {w_s}^2}{g}\right)^{1/3}, \qquad (3)$$

where g is acceleration owing to gravity. This model has successfully been applied to areas with landward fining hurricane deposits in Laguna Playa Grande, Vieques, Puerto Rico (Woodruff *et al.* 2008*b*) and Laguna Madre, Texas, an area where grain size is relatively homogeneous between all cores but large variations in overwash transport distances were quantified (Wallace & Anderson 2010). The success of the advective/settling model is encouraging and suggests that it may be useful in providing additional constraints on the intensity of hurricane flood events where resultant deposits show clear landward fining trends and/or where other evidence exists (such as large transport distances) for settling during horizontal transport with high rates of sedimentation relative to rates of resuspension from the bed.

The above-mentioned inverse-modelling approaches provide techniques for bounding past flooding conditions at a specific site based on resultant event deposits. However, these techniques do not provide direct constraints on storm intensity since flood conditions at a site are influenced by factors additional to storm strength, including location of landfall, storm size, translation speed and angle of approach. Recently, Brandon *et al.* (2013) provide a new technique for inversely modelling storm intensity from grain-size trends within resultant overwash deposits. A large number of synthetic hurricanes generated by the Emanuel *et al.* (2006) down-scaling model are all individually run through storm surge simulations to obtain a time series of offshore changes in water elevation near a site. Each of these time series is then run through an overland flow model to assess the peak bottom shear stress and competence of transport for each storm event. As a case study the technique is applied to sediments collected from Spring Creek Pond, a coastal sinkhole in Northwestern Florida, along Apalachee Bay. Results from these simulations indicate a power-law relationship between the maximum grain size observed in deposits at the site and the most likely hurricane intensity responsible for each deposit, with quantifiable uncertainties that account for variances in flood intensity associated with factors additional to storm strength (storm landfall location relative to the site, storm size, translational speed and angle of approach). Individual grain size v. storm intensity relationships are obtained for incremental changes in the elevation of the site relative to sea-level, such that the inversely modelled wind speed for each deposit in the Spring Creek record accounts for observed sea-level changes over the later Holocene. The Brandon *et al.* (2013) model is skilled in simulated wind speeds for modern deposits when compared with intensities for historical hurricanes affecting the site, and is used to show that all deposits in the reconstruction are capable of being formed by hurricane events. A pre-historic period of increased intense hurricane activity between *c.* 1700 and 600 years B.P. is also evident at the Spring Creek site, which is consistent with the higher resolution reconstruction nearby at Mullet Pond (Lane *et al.* 2011).

Relationship of storm frequency to climate change

Regional shifts observed in palaeohurricane sedimentary archives can be linked to various climatic changes in the geological past, but could also reflect regional-scale controls on hurricane activity. These records can be grouped by their temporal resolutions to better understand regional trends in hurricane overwash. Records of millennial-scale resolution can provide important data regarding the long-term frequency, magnitude and response of hurricanes to lower-frequency climate oscillations. Often, these long-term records reveal fundamental relationships that might be less affected by higher-frequency noise common in shorter-term reconstructions (McCloskey & Knowles 2009). Sites of palaeohurricane reconstructions (Fig. 3) now exist for the western North Atlantic Ocean (Donnelly *et al.* 2001*a*, *b*, 2004; Scileppi & Donnelly 2007; Boldt *et al.* 2010; Kiage *et al.* 2011), northern Gulf of Mexico (Liu & Fearn 2000*a*, *b*; Wallace & Anderson 2010; Lane *et al.* 2011; Brandon *et al.* 2013) and the Caribbean Sea (Bertran *et al.* 2004; Donnelly & Woodruff 2007; Gischler *et al.* 2008; McCloskey & Keller 2009; Malaizé *et al.* 2011; McCloskey & Liu 2012, 2013; Toomey *et al.* 2013*b*; van Hengstum *et al.* 2013). The threshold of storm intensity required for overwash deposition varies significantly between locations and should be considered when making comparisons between sites. Often, the presence of coarse material is used to interpret hurricane deposits. However, there must be a specific grain-size criteria used to establish a threshold, above which is interpreted as a storm and below which is considered fair-weather sedimentation. Sensitivity to overwash varies between sites, and should also be considered when comparing reconstructions. The sensitivity of a barrier to overwash may also change with time. For instance, a high-resolution site from Mattapoisett Marsh, Massachusetts (Boldt *et al.* 2010) offers a unique record of total hurricane impacts above a roughly 2 m inundation threshold. Here, potential changes in site sensitivity owing to barrier transgression have been preserved in overwash sediments. This is reflected mainly in the deposits that become coarser-grained in younger layers. This site therefore captures a wide range of storms, and is not limited to intense events. Regardless of this change in sensitivity, the Mattapoisett Marsh record does contain evidence for additional changes in hurricane occurrences. For instance, the total hurricane deposits have remained relatively constant between *c.* 2200 and 1000 years B.P. However, the last *c.* 800 years B.P. appear to have been a time of relatively frequent total storm deposition (Boldt *et al.* 2010) (Fig. 4).

Other sites along the eastern seaboard of the USA exhibit little to no evidence of potential increases in the sensitivity of overwash related to recent changes in barrier morphology. Based on their timing and overall event counts, this provides support for relatively stable barrier morphologies over the last few millennia for certain sites. Donnelly *et al.* (2001*a*) found evidence of at least seven intense hurricane deposits in Succotash Marsh, Rhode Island over the past *c.* 700 years. Over the same time period, two intense hurricane deposits were found along the southern New Jersey coast (Donnelly *et al.* 2001*b*). Additionally, two prehistoric intense hurricanes were recorded in a sedimentary record from Brigantine, New Jersey in the seventh to fourteenth centuries and the sixth to seventh centuries C.E. (Donnelly *et al.* 2004). At least nine intense hurricane deposits were dated at Alder Island, New York between *c.* 2200 and 900 years B.P. (Scileppi & Donnelly 2007). There is evidence of eight intense hurricane deposits at Wassaw Island, Georgia between *c.* 2000 and 1100 years B.P. (Kiage *et al.* 2011).

Within the Caribbean Sea, a sediment record from a single core from the Blue Hole, Belize, captured 11 major storms from *c.* 645 to 1530 C.E. (Gischler *et al.* 2008). Another record from Gales Point, Belize documented 16 major hurricane

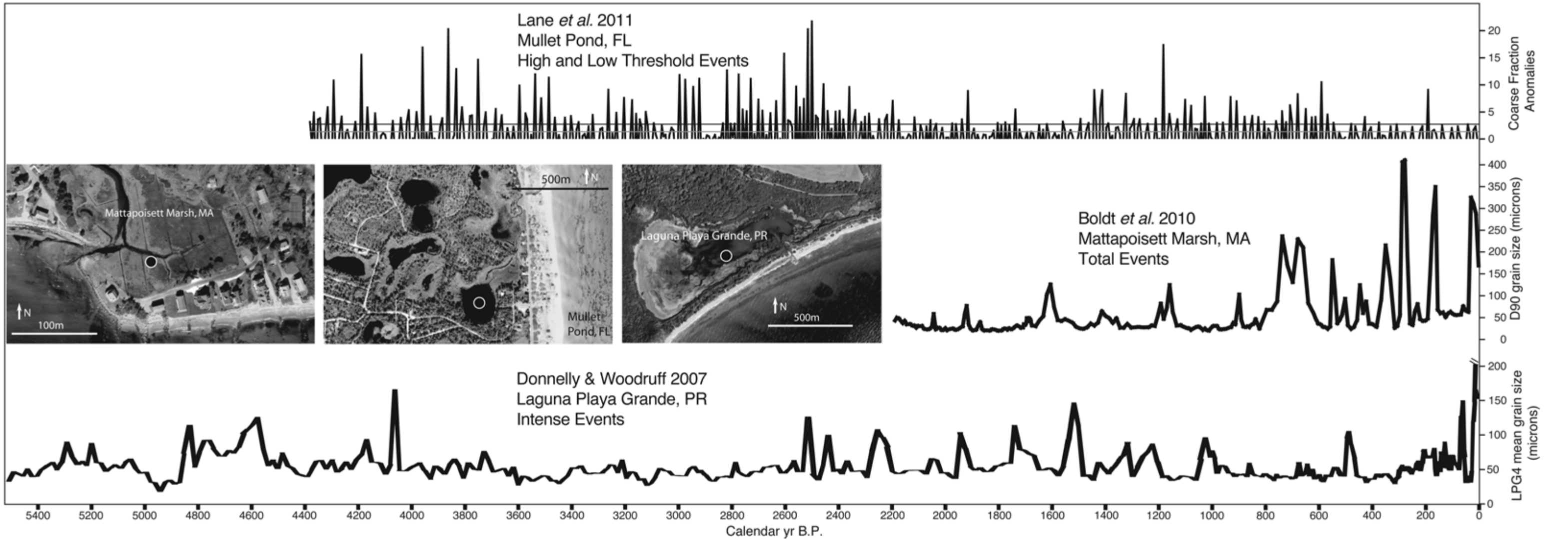

Fig. 4. Compilation of centennial-scale records of sedimentary palaeotempestological overwash proxies over the past *c.* 5500 years B.P. The approximate location of each sediment core (white outlined circle) is shown for each environment (images from Google Earth; data from Scripps Institution of Oceanography, National Oceanic and Atmospheric Administration, United States Navy, National Geospatial-Intelligence Agency, and General Bathymetric Chart of Oceans; see Fig. 3). Storm impacts from Mullet Pond, Florida (Lane *et al.* 2011; high threshold greater than a *c.* 3.3 coarse fraction anomaly, above black line; low threshold greater than a *c.* 1.0 coarse fraction anomaly, above grey line), Mattapoisett Marsh, Massachusetts (Boldt *et al.* 2010; total events) and Laguna Playa Grande, Puerto Rico (Donnelly & Woodruff 2007; intense events). Intense hurricanes (probably of category 4 or greater) frequently impacted Laguna Playa Grande during 4400–3600 and 2500–1000 years B.P. and from 250 years B.P. to present (Donnelly & Woodruff 2007). Periods of frequent intense hurricane strikes (exceeding 3.0 storms per century) occurred between 3950 and 3650, 3600 and 3500, 3350 and 3250, 2800 and 2300, 1250 and 1150, 925 and 875, and 750 and 650 years B.P. at Mullet Pond (Lane *et al.* 2011). At Mattapoisett Marsh, total hurricane impacts appear to have remained relatively constant between *c.* 2200 and 1000 years B.P. However, the last *c.* 800 years B.P. appears to have been a time of relatively frequent total storm impacts (Boldt *et al.* 2010).

events/event clusters in the sedimentary record occurring over the past *c.* 5500 years B.P. (McCloskey & Keller 2009), which displays some correspondence with another major hurricane sedimentary record from coastal Belize (McCloskey & Liu 2013) and Saint-Martin (Bertran *et al.* 2004; Malaizé *et al.* 2011). McCloskey & Liu (2012) determined that five major hurricane events impacted the Nicaraguan coast over the last *c.* 800 years B.P. A sediment core along the Little Bahama Bank showed evidence of nine intense hurricanes from *c.* 1070 to 20 years B.P. (van Hengstum *et al.* 2013). A high-resolution site from Laguna Playa Grande, Puerto Rico has reconstructed intense hurricanes occurring over the past *c.* 5000 years B.P. (Donnelly & Woodruff 2007), with prominent increases in overwash activity observed between 4400 and 3600 years B.P., 2500 and 1000 years B.P., and 250 years B.P. to present (Fig. 4).

In the Gulf of Mexico, different spatial locations in Laguna Madre, Texas record intense hurricane event deposits from *c.* 5300 to 900 years B.P. and provide a long-term, time-averaged annual landfall probability of 0.46%. Periods with preserved hurricane deposits vary between core sites. At one location, six hurricanes are recorded from *c.* 4200 to 1600 years B.P., and another location reveals 10 hurricanes from *c.* 2400 to 1400 years B.P. Two additional core sites contain six hurricane layers from *c.* 3600 to 900 years B.P. and 11 from *c.* 5400 to 2100 years B.P. (Wallace & Anderson 2010). Twelve intense hurricanes left deposits at Western Lake, Florida from *c.* 3500 to 500 years B.P. (*c.* 0.39% annual landfall probability; Liu & Fearn 2000*a*). Lake Shelby, Alabama has evidence of 11 intense hurricane landfalls between *c.* 3500 and 700 years B.P. (*c.* 0.39% annual landfall probability; Liu & Fearn 2000*b*). While the lack of a ^{14}C reservoir correction for Lake Shelby has raised some questions (Lambert *et al.* 2003, 2008), the long-term, time-averaged annual landfall probability remains equal (applying no reservoir correction or applying differential reservoir corrections within the lagoonal and uppermost sediments reveals the same landfall probabilities). Similar long-term annual probabilities between the independent (Liu & Fearn 2000*a*, *b*; Wallace & Anderson 2010) reconstructions suggest that intense hurricane activity over multimillennial periods is similar and has not varied significantly in the Gulf of Mexico (Wallace & Anderson 2010).

An additional Gulf of Mexico record from Mullet Pond, Florida (Lane *et al.* 2011) captures both high- and low-threshold events over the past *c.* 4500 years B.P. (Fig. 4). This record offers some of the highest resolution of available palaeotempestological sites (sub-decadal). While the overall frequency of low threshold events remained relatively constant over the *c.* 4500 years B.P. record, the frequency of high threshold events has varied considerably during this same time interval. At Mullet Pond, several periods of high-threshold intense hurricane activity occurred at or in excess of 3.0 events per century. These periods of frequent intense hurricane strikes occurred between 3950 and 3650 years B.P., 3600 and 3500 years B.P., 3350 and 3250 years B.P., 2800 and 2300 years B.P., 1250 and 1150 years B.P., 925 and 875 years B.P., and 750 and 650 years B.P. (Lane *et al.* 2011; Fig. 4). A millennial-scale resolution *c.* 2500 years B.P. hurricane reconstruction by Brandon *et al.* (2013) nearby at Spring Creek Pond is also consistent with more active intervals of intense hurricane activity occurring between 1700 and 600 years B.P. The most active interval of hurricane activity from the longer Mullet Pond record occurred between 2800 and 2300 years B.P., with hurricane impact rates near 6.0 events per century.

Centennial-resolution studies from the Gulf of Mexico, Caribbean and Atlantic (Fig. 4) provide a means of understanding short-term regional trends of intense and total storm frequency. Over decadal to centennial timescales, the variability between Florida and Puerto Rico might be expected, as high-frequency oceanographic cycles such as loop current penetration in the Gulf of Mexico (Lane & Donnelly 2012; Brandon *et al.* 2013) might be driving these observed differences. Furthermore, high-frequency climate cycles such as ENSO and West African Monsoon could also explain the variability during this time (Donnelly & Woodruff 2007; Toomey *et al.* 2013*b*). However, during the mid-Holocene, hurricane activity also appears to have been dominated by Northern Hemisphere insolation and a northward shift of the Intertropical Convergence Zone (Toomey *et al.* 2013*b*), as rapid atmospheric temperature shifts that occur during ENSO activity could potentially drive hurricanes (Korty *et al.* 2012). These variations appear to be significant, and warrant further research into storm-steering mechanisms over these time intervals and resolutions.

Decadal- to centennial-resolution records (Fig. 4) also provide important data regarding the frequency, magnitude and response of hurricanes to high-frequency climate oscillations that may be especially relevant to human timescales and future hurricane scenarios. The onset of the Medieval Climate Anomaly around 1000 C.E. corresponded with a period probably marked by higher SSTs in the tropical North Atlantic and La Niña-like conditions (Mann *et al.* 2009). Both a statistical model and hurricane sedimentary archive compilation show a peak in hurricane activity during this time at or even higher than present levels of activity

(Mann *et al.* 2009). Following the Medieval Climate Anomaly, relatively lower SSTs and El Niño-like conditions prevailed, and this appears to have diminished hurricane activity.

One of the first efforts to effectively model long-term hurricane activity utilizes simulations over the entire Holocene, rather than direct sedimentological observations that typically only extend back to at most the mid-Holocene. The numerical approach by Korty *et al.* (2012) allows for the ability to test the response of hurricanes to changes in climate independent of varying carbon dioxide, as this was relatively stable between the mid-Holocene and industrial times. Based on these results, it appears that the insolation approximately 6000 years ago may have changed the tropical cyclone potential intensity in the Northern Hemisphere owing to variations in Earth's precession.

In summary, palaeotempestological reconstructions over the past several millennia and accompanying numerical studies reveal: (a) significant variability in tropical cyclone activity in the recent geological past, particularly for the most intense hurricane events; (b) some evidence for synchronous basin-wide changes that are probably forced by changing climatic conditions (not random); and (c) regional differences that could be related to regional controls on formation, track, and/or intensity of hurricanes.

Effects and legacy of palaeohurricanes

The effects of past hurricanes can also provide important information regarding geomorphic changes after hurricane impacts over a variety of timescales. Millennial-scale palaeotempestological records are especially useful for understanding coastal system response to storms. Since the Holocene histories of barrier islands and shoreline systems are often only constrained by millennial-scale resolution changes in evolution, determining the long-term rate of hurricane impacts over these same time periods becomes paramount. One of the most well-studied barrier islands in the world, Galveston Island, Texas, has had a history of progradation from *c.* 5500 to *c.* 1800 years B.P., and retreat following *c.* 1800 years B.P. (Bernard *et al.* 1959, 1970; Rodriguez *et al.* 2004; Wallace *et al.* 2009; Fig. 5). Many of the barriers along the Texas coast have similar transgressive histories (Anderson *et al.* 2010); for instance, Follets Island, a barrier island located directly SE of Galveston, has also been retreating for the past *c.* 2500 years B.P. (Wallace *et al.* 2010). Over this interval of shoreline change the multimillennial rate of hurricane occurrences appears to have remained relatively constant with a return period of once every *c.* 217 years (0.46%; Wallace & Anderson 2010). This might suggest that erosion associated with hurricanes has remained constant. However, spanning the last *c.* 5000 years B.P., the average storm-related offshore sand flux along the upper Texas coast has decreased through time, associated with millennial-scale reductions in sediment supply (Wallace & Anderson 2013) (Fig. 5). This reduction in sediment supply is associated with the exhaustion of the offshore sand body cannibalization process, which supplied the barriers with sand during the Holocene transgression (Anderson *et al.* 2004). These types of long-term observations can be used to constrain evolutionary coastal models operating over long timescales (Storms *et al.* 2002).

Centennial-scale records can be particularly valuable for understanding the natural short-term response of coastal systems to hurricanes. Anthropogenic interventions and modifications immediately following impacts typically alter the normal evolution, such that the natural long-term manifestations are not often observed. After a hurricane impact, coastal flooding can kill trees and plants through saltwater inundation, resulting in an increased dry litter concentration in the forest (Fig. 2). Furthermore, the destruction of the tree canopy can increase insolation and wind speed, resulting in a drier microclimate (Myers & van Lear 1998). Along the northern Gulf of Mexico, fires have been linked with these hurricane impacts over the past *c.* 1200 years B.P. (Liu *et al.* 2008). Palaeotempestological sedimentary proxies were paired with charcoal abundances to reconstruct intense hurricane impacts and fires, and it has been interpreted that fires and vegetation changes immediately followed intense hurricane impacts occurring around *c.* 1170 and 860 years B.P. These results have later been challenged owing to issues concerning: (a) storm deposit thickness v. actual storm intensity; (b) difficulty in assigning ages of fires to within a few years of hurricane occurrence for sites with relatively slow sedimentation rates; and (c) large radiocarbon age uncertainties (Otvos 2009). Nonetheless, the Liu *et al.* (2008) study presents some interesting hypotheses relating storm disruption and resulting environmental impacts that can be tested with future work. For instance, in Central America, a palaeoecological study from Nicaragua also showed that intense fires and vegetation changes occurred after palaeohurricanes (Urquhart 2009). In addition to the potential link between dramatic vegetation changes and increasing fire frequency over short timescales, palaeohurricanes also appear to have caused severe disruption to wetland environments. In New England, palaeohurricane strikes have been linked with significant marsh erosion in the past *c.* 600 years (van de Plassche *et al.* 2006). Following each event, the

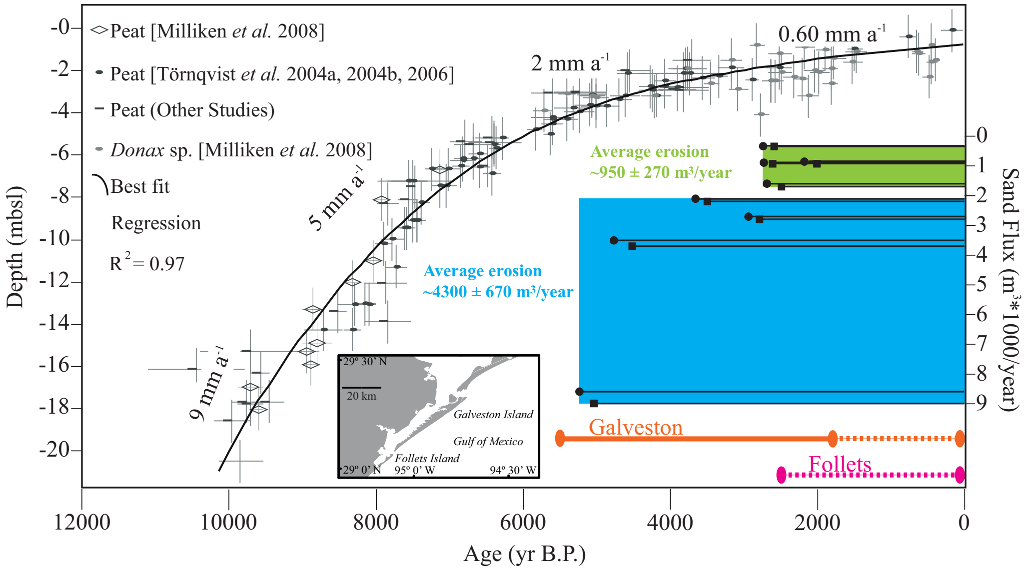

Fig. 5. Palaeohurricane impacts and subsequent erosion through time for the upper Texas coast (modified from Wallace & Anderson 2013). Within the coloured boxes, circles and squares with black lines represent maximum and minimum 2σ ages and associated offshore sand flux, respectively. Each circle and square pair represents individual sediment cores and quantifies erosion along the upper Texas coast following hurricane strikes over the last *c.* 5000 years B.P. Offshore directed barrier island sand erosion shows two populations averaging *c.* 4300 ± 670 m^3/year from *c.* 5100 years B.P. to present (data points inside blue box) and *c.* 950 ± 270 m^3/year from *c.* 2700 years B.P. to present (data points inside green box). Also shown is a sea-level curve for the Gulf of Mexico (figure adapted from Milliken *et al.* 2008 (see this for all included studies and methodologies), with additional data from Törnqvist *et al.* 2004*a*, *b*, 2006). Galveston Island formed 5500 years B.P. and prograded until 1800 years B.P. (solid orange line), when it began to naturally retreat (Bernard *et al.* 1959, 1970; dashed orange line). Follets Islands is a transgressive barrier island that formed about 2500 years B.P. (Wallace *et al.* 2010; dashed pink line). Note that the hurricane induced offshore erosion decreased (green box) during the time when average sea-level rise rates decreased from 2 to 0.60 mm a^{-1}, and occurs not because of fewer storm impacts, but because of decreased sediment supply along the upper Texas coast.

accommodation space created by hurricane-induced erosion was filled by tidal mud, and low and high marsh peat owing to high sediment supply. Thus the study provides an example of the extreme disruption caused by hurricanes to marsh environments, as well as marsh resilience and recovery to these impacts at locations with sufficient sediment supply.

Palaeohurricanes and future research

Palaeotempestological archives are beginning to shed light on links between climate change and hurricane activity, while also providing valuable data for model validation and local risk assessments. Currently, the main limitations of sedimentological palaeotempestological proxies include limited spatial coverage, a lack of a full spectrum of palaeoclimatic records by which to compare hurricane activity records and exact palaeoclimate analogues for future scenarios (Frappier *et al.* 2007*b*). Our understanding of past links between climate and hurricane activity will continue to improve as additional hurricane reconstructions become available and statistical, numerical and laboratory techniques improve for the interpretation of these sedimentary archives. In doing so these records are currently providing, and will continue to provide, a valuable window into past changes in hurricane activity and resulting environmental impacts.

Conclusions

Palaeotempestology studies the past record of hurricanes over a variety of timescales. These records are typically based on sedimentological proxies of tropical cyclone passage preserved in coastal settings. Through careful site selection, alternative depositional mechanisms can be limited that could potentially lead to deposition of coarse-grained material. Quantitative statistical and numerical modelling methods can shed further light on the characteristics of these past events. Temporal and spatial patterns begin to emerge through an analysis of dating uncertainties and statistical significance. However, it is important to maintain an understanding of different palaeotempestological site sensitivities for any record comparisons.

Over the past several millennia, there has been significant variability for the most intense events, with some evidence for basin-wide changes owing to changing climatic conditions. Regional controls on hurricane formation, track and intensity could also account for observed differences between records. These palaeohurricane archives have been especially useful for understanding the long-term evolution of coastal systems owing to hurricane impacts. Additionally, they have provided insight on the response of intense hurricane impacts to low-frequency climate oscillations.

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