Vol 447|24 May 2007|doi:10.1038/nature05834

nature

LETTERS

Intense hurricane activity over the past 5,000 years controlled by El Niño and the West African monsoon

Jeffrey P. Donnelly[1] & Jonathan D. Woodruff[1]

The processes that control the formation, intensity and track of hurricanes are poorly understood[1]. It has been proposed that an increase in sea surface temperatures caused by anthropogenic climate change has led to an increase in the frequency of intense tropical cyclones[2,3], but this proposal has been challenged on the basis that the instrumental record is too short and unreliable to reveal trends in intense tropical cyclone activity[4]. Storm-induced deposits preserved in the sediments of coastal lagoons offer the opportunity to study the links between climatic conditions and hurricane activity on longer timescales, because they provide centennial- to millennial-scale records of past hurricane landfalls[5–8]. Here we present a record of intense hurricane activity in the western North Atlantic Ocean over the past 5,000 years based on sediment cores from a Caribbean lagoon that contain coarse-grained deposits associated with intense hurricane landfalls. The record indicates that the frequency of intense hurricane landfalls has varied on centennial to millennial scales over this interval. Comparison of the sediment record with palaeo-climate records indicates that this variability was probably modulated by atmospheric dynamics associated with variations in the El Niño/Southern Oscillation and the strength of the West African monsoon, and suggests that sea surface temperatures as high as at present are not necessary to support intervals of frequent intense hurricanes. To accurately predict changes in intense hurricane activity, it is therefore important to understand how the El Niño/Southern Oscillation and the West African monsoon will respond to future climate change.

At present there is significant debate about the cause of observed multi-decadal variability of hurricanes in the North Atlantic (for example, see refs 2, 4). To detect long-term patterns in tropical cyclone activity, reliable proxy reconstructions that extend back before the instrumental record are needed. To examine the centennial- and millennial-scale variability of Caribbean hurricane activity and to assess potential climate forcing we reconstruct the history of hurricane-induced overwash events from Laguna Playa Grande (LPG), Vieques, Puerto Rico.

The island of Vieques is located in the northeastern Caribbean Sea (Fig. 1) and is extremely vulnerable to hurricanes. LPG is a hypersaline, backbarrier lagoon separated from the Caribbean Sea by a wave-dominated, sandy barrier 80 m wide and 2–3 m high. The barrier is stabilized on either end by rocky headlands[9] and anchored below by beach rock[10]. Tidal variability is modest (mean range 0.24 m), which minimizes the influence of tidal currents and inlet dynamics. In addition, the relatively slow rates of sea-level rise over the past 6,000 years in the region[11] and the steep topography and bathymetry contribute to barrier stability.

Cores collected from the site contain several metres of organic-rich silt interbedded with coarse-grained event layers comprised of a mixture of siliciclastic sand and calcium carbonate shells and shell fragments. These layers are the result of marine flooding events overtopping or breaching the barrier and transporting these barrier and nearshore sediments into the lagoon. Patterns of coarse-grained event deposits are consistent among all cores (Fig. 2, Supplementary Fig. 1). To determine which historical events left coarse-grained layers at LPG, we developed a detailed age model for the upper 20 cm of LPG12 (Fig. 2). Three coarse-grained deposits are evident in the sediments deposited within the past 100 years. These layers are consistent with three of the most intense hurricanes to strike Vieques over this interval. Seven hurricanes passed within 50 km of the site between 1900 and 2006. Of these, the dates for the two most extreme storms (hurricanes San Felipe in 1928 (category 5) and Hugo in 1989 (category 4)) are consistent with the age of two of the three layers

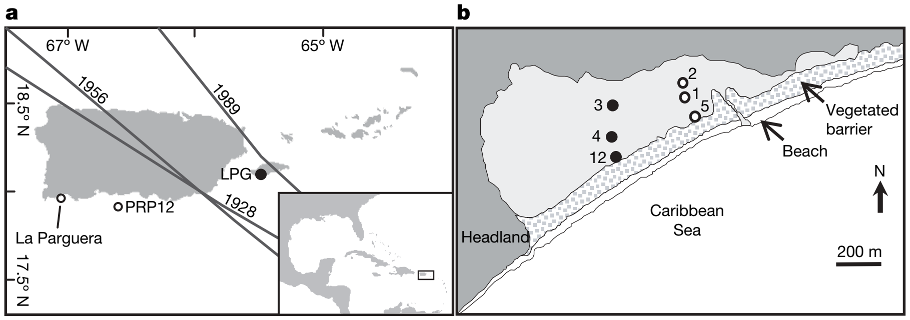

Figure 1 | Site map and core locations. **a**, Map of Puerto Rico with inset map of the tropical Western Atlantic. The location of LPG on the southeastern coast of Vieques is noted with a solid circle. Tracks of the hurricanes mentioned in the text are noted. The location of Puerto Rico (box) is indicated in the inset. Locations of SST reconstructions from La Parguera[17] and PRP 12[16] are noted. **b**, Map of LPG showing core locations (circles). The locations of the cores (LPG12, LPG4 and LPG3) presented in Fig. 2 are noted with solid circles. Cores LPG5, LPG1 and LPG2 included in Supplementary Fig. 1 are also noted.

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[1]Coastal Systems Group, Woods Hole Oceanographic Institution, 360 Woods Hole Road, Woods Hole, Massachusetts 02543, USA.

observed in LPG12 (Fig. 2). Of the less intense storms (categories 1 and 2) only hurricane Betsy (1956) correlates well with the third deposit. However, an analysis of wind damage in eastern Puerto Rico for this particular storm indicates wind speeds more consistent with category 3 intensity[12]. In contrast to the three layers in LPG12, only two layers are preserved in the upper 15 cm of LPG4. The same pattern is evident in cores collected along the easternmost transect (Fig. 1 and Supplementary Fig. 1). The more distal coarse-grained layers in LPG4 were probably deposited by the two most intense hurricanes in the past 100 years (hurricanes San Felipe in 1928 and Hugo in 1989).

Areas of the lagoon adjacent to the barrier (for example, LPG5 (Fig. 2) and LPG12 (Supplementary Fig. 1)) are more likely to experience localized breaching associated with less intense events and are also more susceptible to erosion and truncation of the sediment record during overwash. Conversely, coarse-grained sediments do not always reach the most distal locations (for example, LPG3 (Fig. 2) and LPG2 (Supplementary Fig. 1)) during extreme events, and as a result these areas provide an incomplete record (Fig. 2). The coarse-grained deposits in central locations of the lagoon (for example, LPG4 (Fig. 2) and LPG1 (Supplementary Fig. 1)) provide a relatively complete record of the most intense hurricane (category 4 and greater) strikes, because only these extreme events are capable of producing storm surges high enough to overtop the entire length of the barrier and carry and deposit coarse-grained layers to these locations. Storm-induced deposits within LPG4 reveal large fluctuations in the frequency of intense hurricanes (Fig. 3a). On the basis of our age model (Supplementary Fig. 2) an interval of relatively frequent intense hurricane strikes at Vieques is evident between 5,400 and 3,600 calendar years before present (yr BP, where present is defined as 1950 AD by convention), with the exception of a short-lived quiescent interval between approximately 4,900 and 5,050 yr BP. Following this relatively active period is an interval of relatively few extreme coastal flooding events persisting from 3,600 until roughly 2,500 yr BP. Evidence of another relatively active interval of intense hurricane strikes is evident between 2,500 and approximately 1,000 yr BP. The interval from 1,000 to 250 yr BP was relatively quiescent with evidence of only one prominent event occurring around 500 yr BP. A relatively active regime has resumed since about 250 yr BP (1700 AD).

Evidence of hurricane landfalls in New York indicates periods of activity similar to those of Vieques over the past 2,500 years[13]. In addition, sediment-derived records of intense hurricanes from the Gulf coast also indicate a relatively quiescent interval beginning about 1,000 years ago[5]. The synchronous transition from frequent to infrequent hurricane landfalls in these three regions indicates that a North-Atlantic-wide decrease in hurricane activity occurred about 1,000 years ago and was not simply a change in prevailing hurricane tracks away from the Gulf coast, as has previously been suggested[5,14].

Warm sea surface temperatures (SSTs) in the tropical North Atlantic are thought to be a key ingredient for fuelling intense hurricanes[1,15] and are at the centre of the debate over the impact of global warming on tropical cyclone activity. Unfortunately, few reconstructions of SST spanning the past 5,000 years from the main development region (MDR) for hurricane formation (Supplementary Fig. 3) are available. However, SST reconstructions from off Puerto Rico (PRP12[16] and La Parguera[17]; Fig. 1a) are probably good proxies for the MDR (Supplementary Fig. 3). The PRP12 reconstruction indicates that summer SSTs in the tropical North Atlantic have generally been cooler than at present, varying by as much as 2 °C (roughly 26–28 °C) over the past 2,000 years (Fig. 3b)[16]. In addition, coral-based SST reconstructions from La Parguera, Puerto Rico (Fig. 1a), indicate that mean annual Little Ice Age (250–135 yr BP or 1700–1815 AD) SSTs were 2–3 °C cooler than they are now (Fig. 3b)[17]. Despite cooler Little Ice Age SSTs in the region, the sediment record from LPG and New York[13] indicates an increase in intense hurricane landfalls since about 1700 AD (250 yr BP) (Fig. 3b).

Historical records from Puerto Rico also suggest an increase in severe hurricane damage in the 18th and 19th centuries. Only three storms are documented as resulting in severe damage (≥F2 on the Fujita scale) in Puerto Rico between 1550 and 1700 AD, while at least sixteen severe hurricanes affected Puerto Rico between 1700 and 1850 AD[12]. Although the historic archives may be less complete during the early part of these records and so some hurricanes may have gone unrecorded, sediment-based reconstructions are unaffected by this type of biasing. Therefore, the good agreement between the sediment-based reconstructions and the historic archives strongly suggests that the frequency of intense hurricanes increased at around 1700 AD. In addition, an analysis of Caribbean hurricanes documented in Spanish archives indicates that 1766–1780 was one of the most active intervals in the period between 1500 and 1800 AD (ref. 18), when tree-ring-based reconstructions indicate a negative (cooler) phase of the Atlantic Multidecadal Oscillation[19]. Furthermore, the sediment record from LPG indicates that an interval of relatively frequent intense hurricane strikes persisted for over a millennium (2,500 to 1,000 years ago) despite cooler-than-modern SSTs. Thus the information available suggests that tropical Atlantic SSTs were probably not the principal

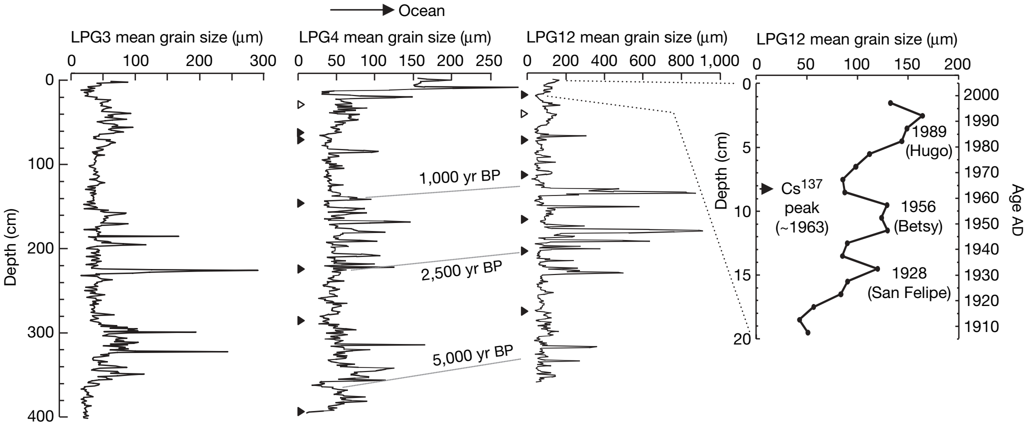

Figure 2 | Bulk grain-size data revealing storm-induced deposits. The mean grain-size scale is set at 250 and 300 μm for LPG4 and LPG3, respectively, because the coarse-grained layers are generally finer in these more distal locations. Solid arrows represent the depth of radiocarbon-dated samples from LPG4 and LPG12. The depth of abrupt increase in Ti and Fe associated with land clearance at approximately 1840 AD (110 yr BP) is noted with an open triangle. Dashed grey lines indicate depths of equal age between LPG4 and LPG12, based on the age models presented in Supplementary Fig. 2. The enlarged upper 20 cm mean grain-size plot of LPG12 (far right) with an age model based on an accumulation rate of 2 mm yr^{-1} is derived from Cs^{137} data and evidence of land clearance (~1840 AD). Deposits attributable to documented hurricanes are noted. The arrow above plots indicates the direction of the ocean relative to core sites.

driver of intense hurricane activity over the past several millennia; however, more high-resolution records of SSTs, including depth of the mixed layer, are required to address the role of SSTs on intense hurricane activity over this period adequately.

Studies relying on recent climatology indicate that North Atlantic hurricane activity is greater during La Niña years and suppressed during El Niño years[20,21], due primarily to increased vertical wind shear in strong El Niño years hindering hurricane development. A comparison between LPG4 and a proxy record of El Niño events from Laguna Pallcacocha, Ecuador[22], suggests that the evolution of El Niño/Southern Oscillation (ENSO) variability has also played a key part in governing Atlantic intense tropical cyclone activity for much of the past 5,000 years (Fig. 3). For example, intervals of frequent intense hurricane strikes at LPG (for example, $\sim$2,500 to 1,000 yr BP, 3,600 to 4,400 yr BP, and 250 yr BP to present) correspond primarily to periods with relatively few El Niño events. Conversely, periods with more frequent, strong El Niño events generally correspond to periods with fewer intense hurricane strikes on Vieques (for example, $\sim$3,600 to 2,500 yr BP and 1,000 to 250 yr BP) (Fig. 3c). A possible exception to this correlation is the interval between 4,600 and 5,000 yr BP; however, a small ($\sim$100–200 years) shift within the uncertainty range of the age model in either record would also result in the lull in El Niño events corresponding to the active hurricane interval here.

In addition to the El Niño record there is also a strong correspondence between a precipitation record from Lake Ossa, West Cameroon (Fig. 3d)[23], and the record of intense hurricane activity from Vieques. Intervals of increased precipitation (thought to result from more frequent convective storms) in tropical Africa correspond to times of increased frequency of intense hurricanes recorded at LPG. Conversely, less convective storminess in tropical Africa appears to be associated with relatively few intense hurricanes in the Western Atlantic. The amount of precipitation in tropical Africa is probably related to the strength of the West African monsoon. This correlation between tropical African precipitation and North Atlantic hurricanes is consistent with recent findings[24] linking periods of increased hurricane activity in the middle of the 20th century with increased monsoonal strength in Africa and a well-developed African easterly jet. Increased cyclonic vorticity in the MDR results from a well-developed African easterly jet. During intervals of increased monsoonal strength (with a well-developed African easterly jet) and cool ENSO phase, African easterly disturbances (waves) pass through a region of enhanced cyclonic vorticity, warm SSTs, and low vertical shear, enhancing the development of hurricanes in the central and western portions of the MDR.

Increases in precipitation in tropical Africa are a likely positive feedback mechanism contributing to the formation and enhancement of the African easterly jet by increasing the soil moisture gradient[25]. The negative correlation between precipitation proxies in West Cameroon and Ecuador may also point to ENSO modulation of the West African monsoon. In fact, El Niño events combined with

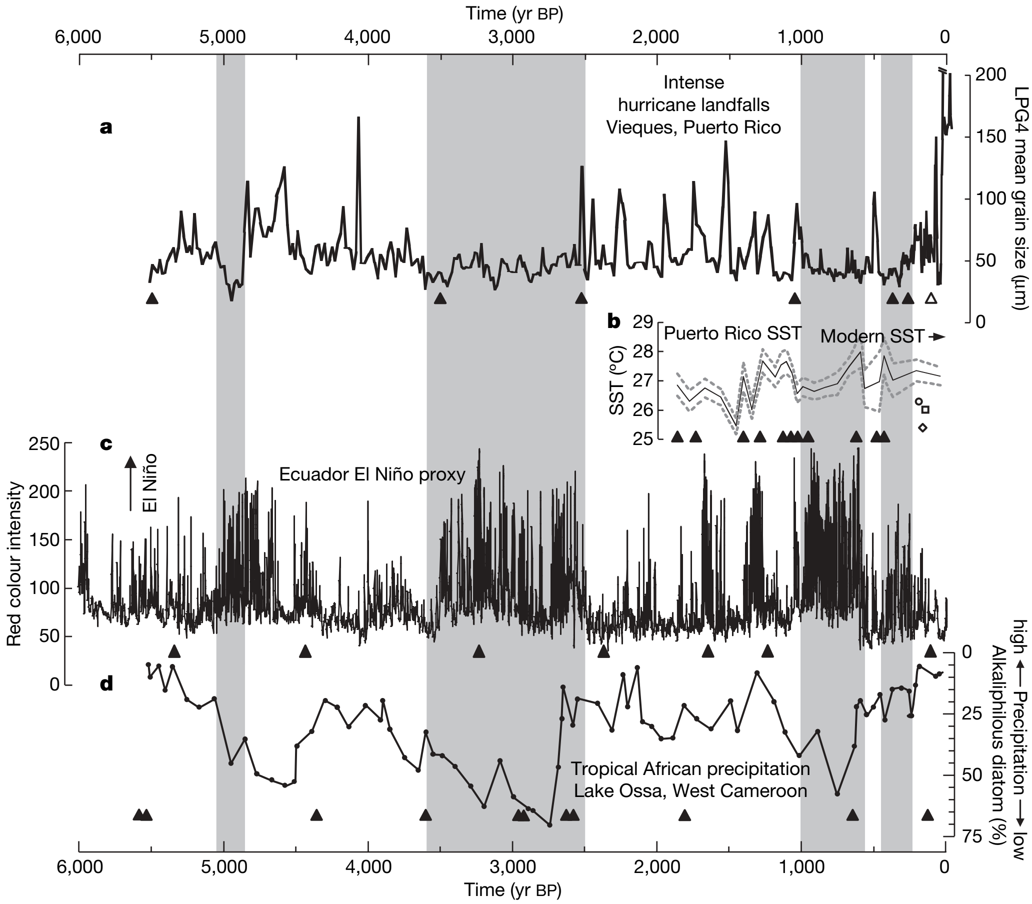

Figure 3 | Comparison of the intense hurricane record from LPG with other climate records. **a**, Mean bulk grain-size record from LPG4. Intervals of relatively few intense-hurricane-induced layers in all cores are noted with shading. **b**, The thin line with the 2σ uncertainty envelope (dashed lines) is a reconstruction of summer SSTs off Puerto Rico[16] (core PRP12) and coral-based reconstruction of mean annual SSTs from La Parguera, Puerto Rico[17], are noted: 26.2 °C for 1700–1705 AD (circle), 25.3 °C for 1780–1785 AD (diamond), and 26.0 °C for 1800–1805 AD (square). The modern mean annual SST is noted with an arrow. **c**, El Niño proxy reconstruction from Laguna Pallcacocha, Ecuador[22]. Peaks in red colour intensity are documented as allochthonous material washed into the lake primarily during strong El Niño events. **d**, Changes in precipitation in West Cameroon inferred from alkaliphilous diatoms (thriving in alkaline conditions) from Lake Ossa[23]. Radiocarbon age control points are noted with black arrows below all panels.

negative SST anomaly in the eastern equatorial Atlantic have been linked to drought in western Africa[26]. However, controls on eastern equatorial Atlantic SST fluctuations independent of ENSO may also have played an important part in modulating the intensity of the West African monsoon over the Holocene epoch[27].

A coherent pattern of climate change over the past 5,000 years appears to have modulated intense hurricane activity in the north-eastern Caribbean. The evolution of ENSO variability over the past several millennia probably played an important part in controlling the frequency of intense hurricanes in the Caribbean and perhaps the entire North Atlantic Basin, with intervals of fewer strong El Niño events resulting in less vertical wind shear over the tropical North Atlantic and more favourable conditions for intense hurricane development. In addition, variations in the West African monsoon and African easterly jet probably also play a critical role in modulating the frequency of North Atlantic intense hurricanes, with increases in convective storms over tropical Africa leading to stronger easterly waves moving into the tropical North Atlantic. Given the increase of intense hurricane landfalls during the later half of the Little Ice Age, tropical SSTs as warm as at present are apparently not a requisite condition for increased intense hurricane activity. In addition, the Caribbean experienced a relatively active interval of intense hurricanes for more than a millennium when local SSTs were on average cooler than modern. These results suggest that in addition to fluctuations in tropical Atlantic SST, changes in atmospheric dynamics tied to ENSO and the West African monsoon also act to modulate intense hurricane activity on centennial and millennial timescales. A better understanding of how these climate patterns will vary in the future is therefore required if we are to predict changes in intense hurricane activity accurately.

METHODS

Cores were collected using a Vohnout/Colinvaux piston corer in 5-cm-diameter polycarbonate barrels. Short 10-cm-diameter push cores were taken at select core locations to capture the sediment/water interface better and to provide adequate material for radio-isotopic analyses. These push cores were extruded in the field and sampled every 0.5 cm. Measurements of the activity of Cs^{137} (a product of atmospheric nuclear weapons testing) were conducted using a high-resolution gamma detector. The locations for all coring sites were determined using a handheld GPS unit which provided a horizontal accuracy of 3 to 6 m. Sediment cores were split in the laboratory and selected core halves were run through a non-destructive Itrax core scanner to obtain millimetre- to submillimetre-resolution X-ray fluorescence measurements of the sediment's elemental composition, on the basis of methods described in ref. 28. Bulk grain-size analysis was conducted on contiguous 1-cm samples using a Beckman-Coulter LS13320 laser diffraction particle-size analyser. As the bulk mean grain-size data represent siliciclastic, organic and calcareous material of varying densities, the relative magnitude of events cannot be directly inferred by comparing values for individual coarse layers. Samples of wood, seeds and shells were radiocarbon-dated at the National Ocean Sciences AMS Facility at Woods Hole Oceanographic Institution. The resulting radiocarbon ages were calibrated to calendar years using the IntCal04[29] and Marine04[30] calibration data sets (Supplementary Table 1).

Received 21 November 2006; accepted 10 April 2007.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements Funding for this research was provided by the National Science Foundation, the Risk Prediction Initiative, the National Geographic Society, the Coastal Ocean Institute at Woods Hole Oceanographic Institution, and the Andrew W. Mellon Foundation Endowed Fund for Innovative Research. We are grateful to E. Bryant, E. Scileppi, J. Tierney, and A. Jovanovic who assisted with the field and laboratory work. E. Uchupi and P. Lane provided advice and D. Oppo, J. Russell, T. Webb III, K. Emanuel and L. Giosan made suggestions for improving this manuscript. This is a contribution of IGCP 495—'Holocene land-ocean interactions: driving mechanisms and coastal responses'.

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