SCIENTIFIC REPORTS

OPEN

SUBJECT AREAS:
GEOLOGY
ATTRIBUTION
PALAEOCEANOGRAPHY
PALAEOCLIMATE

Received
19 June 2013

Accepted
6 January 2014

Published
27 January 2014

Correspondence and requests for materials should be addressed to K.C.D. (kdenom1@lsu.edu)

Climatic controls on hurricane patterns: a 1200-y near-annual record from Lighthouse Reef, Belize

K. C. Denommee[1,2], S. J. Bentley[1,2] & A. W. Droxler[3]

[1]Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA, 70803, USA, [2]Coastal Studies Institute, Louisiana State University, Baton Rouge, LA, 70803, USA, [3]Department of Earth Sciences, Rice University, Houston, TX, 77005, USA.

Tropical cyclones (TCs) are powerful agents of destruction, and understanding climatic controls on TC patterns is of great importance. Over timescales of seasons to several decades, relationships among TC track, frequency, intensity and basin-scale climate changes are well documented by instrumental records. Over centuries to millennia, climate-shift influence on TC regimes remains poorly constrained. To better understand these relationships, records from multiple locations of TC strikes spanning millennia with high temporal resolution are required, but such records are rare. Here we report on a highly detailed sedimentary proxy record of paleo-TC strikes from the Blue Hole of Lighthouse Reef, Belize. Our findings provide an important addition to other high-resolution records, which collectively demonstrate that shifts between active and inactive TC regimes have occurred contemporaneously with shifts hemispheric-scale oceanic and atmospheric circulation patterns such as MDR SSTs and NAO mode, rather than with changes in local climate phenomena as has previously been suggested.

Tropical cyclones (TCs) are among the most catastrophic atmospheric phenomena in terms of their potential to cause loss of both life and property[1]. In light of this, much effort has been put into studying how TC regimes might change under anthropogenic increase in atmospheric greenhouse gas (GHG) concentrations and related global warming - often with conflicting results[2,3]. For the most recent decades, we possess comprehensive instrumental records and research has documented relationships among TC track, frequency and intensity, and key aspects of basin-scale climate changes over seasonal to decadal timescales[4–7]. In order to better understand the mechanisms driving long-term variations in TCs we require records of TC strikes that span periods exceeding the instrumental record, ideally at near-annual temporal resolution; unfortunately, such records are rare. Here we report on a highly detailed sedimentary proxy record of paleo-hurricane activity from the Blue Hole of Lighthouse Reef in Belize, one of the only records from the Caribbean basin that possesses near-annual temporal resolution of TC strikes (Fig. 1). This proxy record provides a unique contribution to the paleo-storm record, filling in a much needed gap in our understanding of Western Caribbean TC regimes; filling this knowledge gap may help answer important questions regarding local versus basin-wide climate controls on Caribbean and Gulf of Mexico TC frequency. This work builds and improves on a previous study that established the sub-annual temporal resolution of normal background sedimentation in the Blue Hole and the exceptional preservation potential of event-layers deposited by the passage of TC strikes[8].

A recent comparison of continuous, high-resolution (e.g., decadal or better resolution) paleo-hurricane records for the Western Atlantic, eastern Caribbean, and northeast GoM coasts has suggested that basin-scale climatic patterns have controlled Atlantic Basin TC track, frequency, and intensity over century timescales and longer[9]. However, other studies have suggested that TC strike frequencies may be influenced more by local climate phenomena than hemispheric-scale forcing[10]. This uncertainty and our inability to understand long-term hemispheric patterns in TC track, frequency, and intensity cannot be resolved without additional high-resolution TC records from the Caribbean - especially from the western Caribbean that, at present, lacks good representation. Sediment cores, collected from the Blue Hole of Lighthouse Reef, Belize, an anoxic sinkhole located on an offshore isolated carbonate platform in the Mesoamerican Barrier Reef Complex (Fig. 1), contain an undisturbed record of sub-annually resolved sedimentation produced by a combination of fair-weather infilling and tropical cyclone strikes (tropical storms, major and minor hurricanes)[8]. This newly acquired archive of tropical-cyclone-driven event sedimentation records the impacts of tropical cyclones over the last 1200 y, providing the most continuous

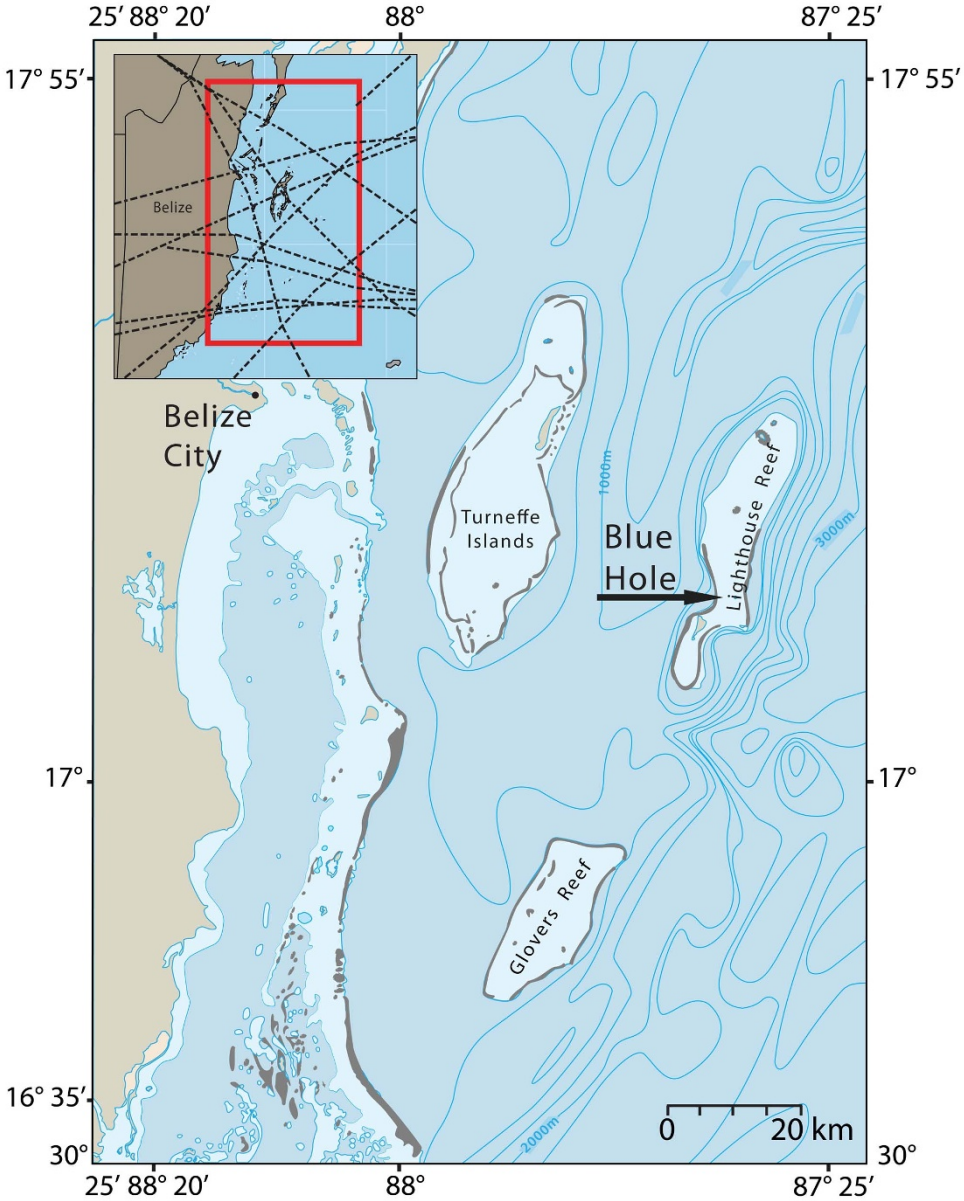

Figure 1 | Geographical location of the Blue Hole on Lighthouse Reef, an isolated platform surrounded by deep water, 100 km offshore the Belize coastline. Inset details tropical cyclone tracks (1996–1945) passing within 100 km of the Blue Hole[11]. Bathymetric contours 0 m, 100 m, and 500-m intervals below 500 m below sea level. This figure was produced by the corresponding author by the digitizing a nautical chart of the coast of Belize in Adobe Illustrator. The hurricane tracks were downloaded from NOAA HURDAT and superimposed over the digitized map. The figure was produced using US government data (HURDAT) and US Defence Mapping Agency chart 28167. Under section 101 of the US Copyright Act, these documents and data sets are not entitled to domestic copyright protection, and the US DMA does not assert copyright protection over its nautical chart products.

and thoroughly dated, sub-annually resolved record of TC activity for the Caribbean to date. This record will allow us to more reliably evaluate the mechanisms driving long-term variations in TC regimes in the Caribbean Basin, and consequently better understand the mechanisms driving long-term variations in TCs within the North Atlantic Basin. We hypothesize that, if the latest Holocene record of TC strikes preserved in Blue Hole sediments is largely controlled by local climatic and oceanographic conditions, then the Blue Hole TC record should be generally decoupled from elsewhere in the Gulf of Mexico and Caribbean Sea. Conversely, if Gulf of Mexico and Caribbean TC activity is largely driven by basin-wide climate and oceanographic conditions, then the timing of hurricane regime shifts should correspond to major documented shifts in basin-scale climate and oceanographic forcing mechanisms such as sea surface temperatures (SSTs) from the main development region (MDR) for Atlantic hurricanes and persistent shifts in the phase of the North Atlantic Oscillation (NAO) index.

Results

The results of this study are anchored on a robust age/depth framework, based upon an AMS ^{14}C age model that shows a very strong correlation with an independent age model determined by counting annual couplets. The layer-counting approach was validated previously for this location[8], although our radiometric age model shows a constant age offset of −339 y, compared to the layer-counting model (Fig. 2). Excess ^{210}Pb is found throughout the upper portions of the Blue Hole sedimentary sequence, to at least a depth of 63 cm (Fig. 2) and suggests that the uppermost seabed materials were deposited during a time interval equal to or less than the last 110 y (or ~five times the ^{210}Pb half-life of 22.3 y). The consistency of the age offset

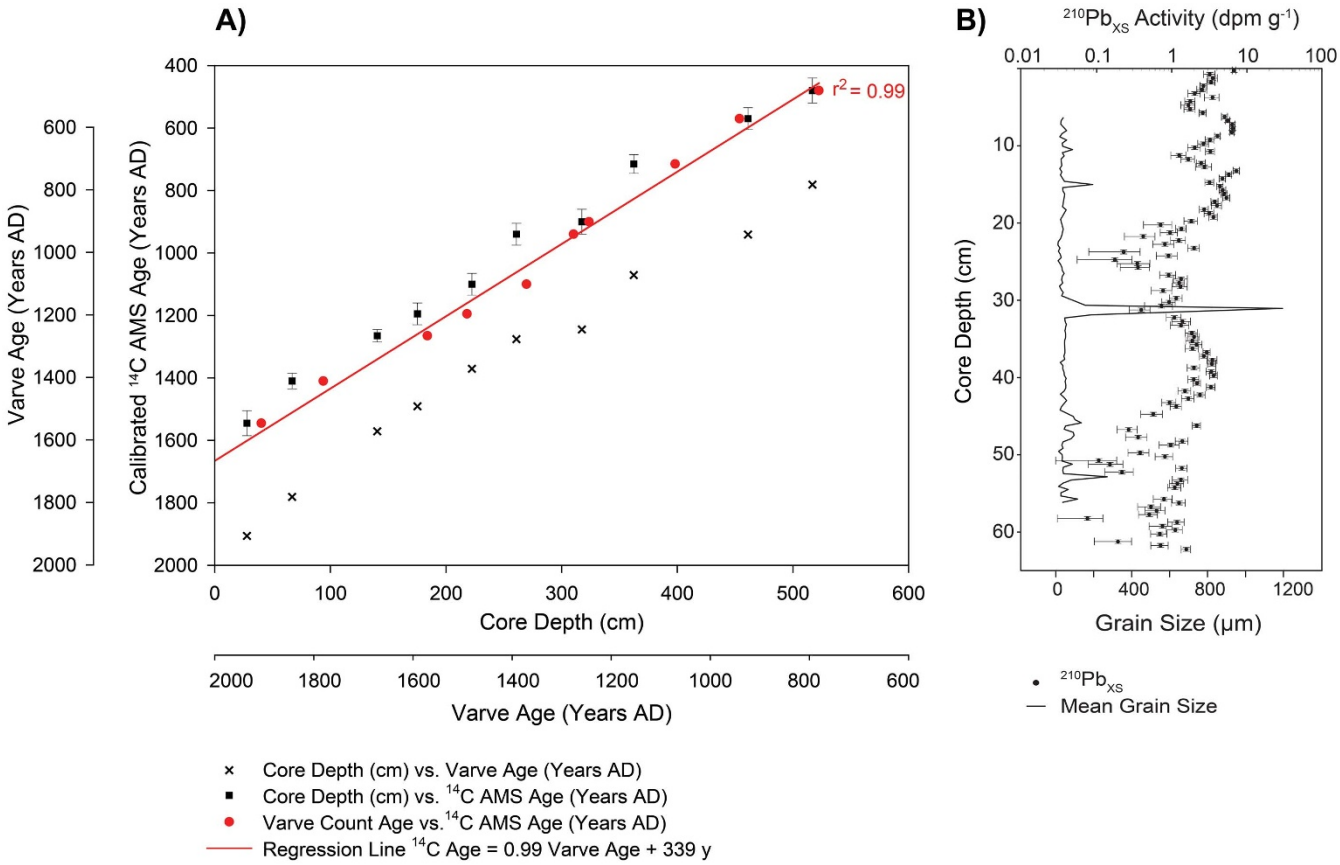

Figure 2 | (A) Combined plot of sediment age (Years AD) vs. depth in core (cm) as determined by both calibrated ^{14}C AMS geochronology and by varve counting and plot of calibrated ^{14}C AMS age vs. varve-count age (Years AD). (B) $^{210}Pb_{XS}$ and mean grain-size profile for sediment gravity core BZE-BH-GC2. The lack of a log-linear decrease of ^{210}Pb with depth and the evident variability of ^{210}Pb activity with depth suggests that sediment properties and/or sediment accumulation rates have varied sharply over time. This is consistent with event sedimentation such as that caused by tropical cyclones. This variability however, also prevents calculation of sediment accumulation rates using common methods that require (near) steady-state depositional processes[30,34].

between the layer-counting and ^{14}C age models in combination with the presence of $^{210}Pb_{XS}$ indicate that this constant temporal offset represents a reservoir effect linked to an older source of ^{14}C within the system that has yet to be documented at this particular site, and does not represent a hiatus at the top of or within the sedimentary record.

Core stratigraphy includes two classes of sediment layers: fine-grained couplets (mean grain size 10–30 µm) <2.5 mm thick each comprised of one buff-coloured and one green-coloured lamina, and thicker (>2.5 mm), coarser-grained layers (mean grain size > 30 µm) (Fig. 3). The previous Blue Hole study identified the couplets as annual sediment layers, and the thicker, coarser-grained layers as being TC-generated sedimentary event layers[8]. In order to evaluate probable mechanisms for formation of these thick event layers, the known chronology of historical TCs passing within 100 km of Lighthouse Reef was compared with the distribution of event layers observed in sediment cores during the same time period (Fig. 1 inset; Table 1)[11]. Of the 13 documented tropical systems (intensity ≥ tropical storm) recorded in the vicinity of the Blue Hole, nine were matched to event layers near the anticipated core depth, with an age offset from layer counting of −0.4 ± 2 y with respect to the known age of the event. Four historically documented tropical systems were not recorded in the core near the anticipated depth in the sediment, including three tropical storms and one Category 1 hurricane (Table 1). One event layer preserved in the sediment did not match the age of any known TCs (Table 1). For TCs not recorded in the sediment core, it is likely that these storms were not detectable because they lacked the necessary energy to induce storm sedimentation (overwash) at the study location due to a combination of distance from the Blue Hole and/or local wave intensity. Because the comparison of the proxy record based on the sedimentary character of TC-generated event layers to the record of known storms does not generate a perfect match, missing ~23% of known events, we must consider this to be the minimum uncertainty associated with the record.

The study site is located ~200 km north of the active strike-slip zone along the Caribbean/North American plate boundary, so we considered the potential of seismic events as mechanisms for the deposition of overwash sedimentary event layers. Unfortunately there are no widely applicable diagnostic criteria to distinguish storm versus tsunami-generated event beds in such a depositional setting. However, the far-field tsunami potential for the Belize coast is low[12] and estimated earthquake return period for the region is relatively long (>150 y), especially when compared to anticipated TC return periods; so that seismically assciated event beds, if present at all, could only account for a small fraction of the many events recorded in the Blue Hole.

Based on the strong correlation between the age and depth of observed event layers and the known timing of historical TCs, and the long return period of potential tsunami-generated event layers, thick event layers are interpreted to be formed by TCs, with a detection uncertainty of 23%. Although TC event layers are distinguishable from annual couplets by grain size, colour, and layer thickness, our evaluation of the historical portion of the core indicates that layer thickness is a sufficient recognition criterion to make this distinction.

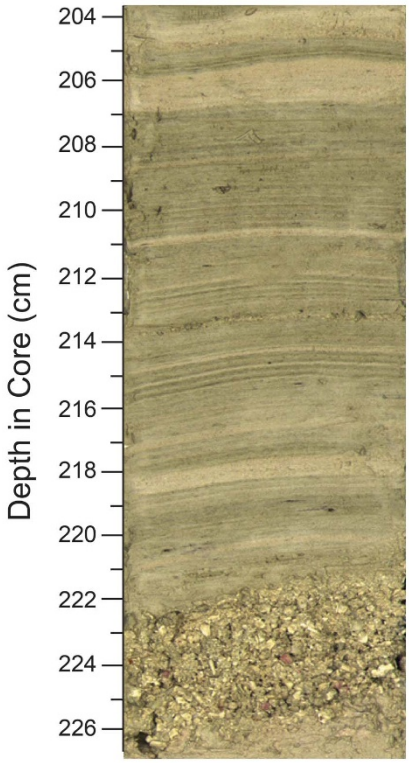

Figure 3 | Representative photo of the Blue Hole sediment core (204 – 226 cm interval of vibracore BZE-BH-SVC4). The normal background sedimentation consists of fine-grained, buff/green laminated calcium carbonate couplets (~2.5 mm in thickness). The laminations reflect variations is organic matter content of the sediment resulting from seasonal variations in the organic productivity of Lighthouse Reef lagoon surface waters[8]. TC-event layers can be distinguished from this normal background sedimentation on the basis of grain-size, layer thickness, and colour[8].

As proxy for TC frequency, we present detectable event return period averaged over 100 y (T_{100}), with T_{100} mean and standard deviation over the entire record of 11 ± 6 y (Fig. 4). From ca. 800–1350 AD, an interval corresponding to the Medieval Climate Anomaly (MCA) that is characterized as the most recent pre-industrial warm interval[13], the Blue Hole sediments record the most active period of TC activity in our proxy record. During this interval we observe T_{100} of 4 – 7 y, reaching the shortest T_{100} during this interval ca. 900–1000 AD y BP (i.e., highest TC frequency; Fig. 4). In contrast there is an abrupt decrease in the frequency of recorded TC events beginning ca. 1400 AD, near the onset of the Little Ice Age[14] during which we observe a sustained lull in TC activity that lasts until ~1900 AD (Fig. 4). This is followed by an upswing in TC activity that extends until present day, with the T_{100} approaching 7 y - nearing activity levels observed during the MCA. We interpret these results to mean that the interval corresponding to the MCA was a time of high TC frequency, as have been the past 100 y, and that the interval corresponding to the LIA was a time of reduced TC frequency.

Previous studies have relied upon grain size for estimates of relative intensity. However, in the present case, event-layer thickness is likely to be a more sensitive indicator of hurricane combined intensity and duration than grain size. This is because the coarsest sediment on the reef top that is found in our cores is readily resuspended by waves generated from the winds of even the weakest TCs. From linear wave theory[15], a weak Category 1 hurricane with wind blowing 32 m/s over a 10 km fetch and water 3 m deep can generate local waves of 0.85 m height and 3.3 s period. Bed shear stresses from these waves reach ~3.7 Pa, sufficient to resuspend calcite spheres ~5 mm in diameter. In contrast, the coarsest grains in our cores are lower-density flakes from the calcareous green alga *Halimeda*, up to ~4 mm in maximum dimension (Corey shape factor ~0.2), with theoretical critical shear stress for resuspension on the order of 2 Pa[16,17]. These calculations do not take into account currents or propagation of swell across the reef surface, which would be likely to result in even greater bed shear stresses produced by minimal TCs. It is likely that stronger TCs would produce stronger bed shear stresses, but the peak grain size recording the event could be limited by the size of sediment available for transport. In contrast, bedload sediment transport rate is generally considered to be a power function of the amount by which local bed shear stress exceeds critical shear stress for grain transport[15,17]. As a result, the bedload transport rate can continue to increase due to increasing wave-current intensity (even if sediment grain size does not increase appreciably during a storm), and can persist as long as shear stresses remain high and sediment is available for resuspension.

Discussion

With sub-annual resolution recording a mean storm recurrence of ~12 TCs per century, the Blue Hole is a unique and faithful archive of paleo-hurricane and tropical storm strikes for the Western Caribbean. Although uncertainty of detection is ±23% per event, mostly for TCs of tropical storm intensity, this proxy record appears

Table 1 | A comparison of historical tropical systems (1945–1996) passing within 100 km of the study location[11] (Intensity ≥ Tropical Storm). The upper ~3 cm of core material is disturbed and no correlations were made for this interval

Storm Name	Maximum Intensity at Sampling Location	Strike Year	Core Record Year
Kyle	TS	1996	1996
Gert	TS	1993	1992
--	--	--	1987
Hermine	TS	1980	Not Observed
Greta	H4	1978	1979
Edith	H1	1971	1973
Laura	TS	1971	Not Observed
Francelia*	H2	1969	1969
Hattie	H5	1961	1961
Abby	H1	1960	Not Observed
Gilda	TS	1954	Not Observed
Not Named	TS	1946	1948
Not Named	TS	1945	1945
Not Named	H1	1945	1945

*This storm falls outside the 100 km search radius but the event is possibly represented in the sediment core.

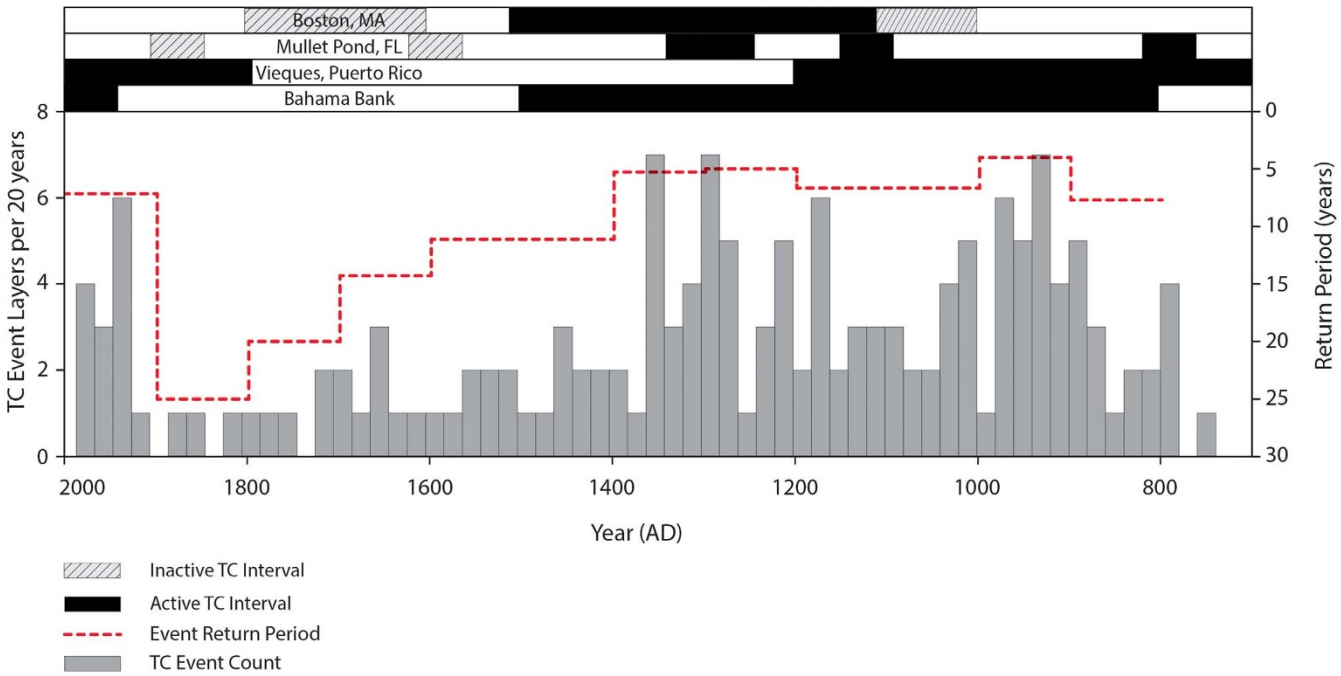

Figure 4 | (Lower Panel) Total of all detected event layers per 20 y period (gray histogram), 100 y averaged event-return period (red dash, T_{100}, y). (Upper Panel) Select, high-resolution sedimentary records of land falling hurricanes are presented for the Atlantic Basin including New England (Boston, MA)[23], the Florida Gulf Coast (Mullet Pond, FL)[25], the Eastern Caribbean (Vieques, PR)[24], and the Bahamas[26].

to have the finest temporal resolution (the only near-annual record), and continuity (a single record with no apparent hiatuses) of all TC proxy records from the Western Caribbean. Our results show that this archive records strikes of TCs from tropical storm to major hurricane intensity, not only major hurricane (H4 and H5) activity as has been previously reported[18], and show evidence for three distinct Caribbean TC (frequency) regimes over the past 1200 y. Although TC activity is observed throughout the entirety of the time period represented in our sediment cores, the results of this study unequivocally demonstrate that the development of hurricanes affecting the western Caribbean has varied over centennial timescales (Fig. 4). The hurricane-strike frequency distribution we present is broadly consistent with the findings of a previous study from the Blue Hole[8]. However, we offer improved resolution and detection of relatively weak TC events, quantitative time-series analysis, and an age model with reduced uncertainty as compared to this previous study. We note that our TC frequency distribution is inconsistent with a recent study of TC strikes from the coastal mainland of Belize that attributed variations in TC strike frequency to local climate phenomena[10]. Recording only five likely TC events layers in sediments younger than 256 y b1950, the mainland study is not calibrated to the modern instrumental record and has significantly lower temporal resolution and site sensitivity than our Blue Hole sedimentary proxy record.

Our proxy record demonstrates that the timing of observed major shifts in hurricane frequency and event layer thicknesses in the Western Caribbean occur contemporaneously with documented shifts in basin-scale climate phenomena (Fig. 5). As such we interpret the centennial-scale variations in TC frequency in terms of shifts in documented basin-scale climatic patterns that are understood to drive TC frequency variability in the Caribbean including; (1) the NAO that influences the tracking of TCs through shifting North Atlantic Basin atmospheric pressure gradients[19], and by association the favourability of the thermodynamic environment that they encounter[20]; and (2) SSTs from the MDR for Atlantic hurricanes (10–14° N, 20–70°W) that affect the favourability of the thermodynamic environment and the vertical wind shear and tropospheric stability of the environment of TC development[21].

We observe increased TC activity between ~800 and ~1350 AD, corresponding to the MCA, a time period during which widespread indices of climatic shift have been observed[22]. Among these indices are a persistently positive NAO index and changes (warming) of SSTs (Fig. 5) both of which are conducive to the development and intensification of TCs. Conversely during the LIA, we see evidence of persistently negative NAO indices and cooler MDR SSTs, indicative of climatic shift towards unfavourable TC development conditions (Fig. 4).

The Blue Hole proxy TC record fills a spatial gap in regional coverage of TC records, with the finest temporal resolution of TC proxy records for the western Caribbean Sea. Figure 4 compares the Blue Hole proxy record to other records of comparable temporal resolution[23–26], and demonstrates that active periods for TCs for the western Caribbean are consistent not only across the greater Caribbean/Gulf of Mexico region, but also across much of the Atlantic Basin supporting the idea that centennial-scale paleo-TC activity has indeed varied at the basin scale[9]. Timing of shifts in hurricane activity levels recorded in Blue Hole sediments appear to be contemporaneous with variations observed in other paleo-storm archives, and also with documented centennial-scale shifts in climatic conditions (including the mean NAO index and MDR SSTs) known to affect the development and intensity of TCs (Fig. 5). Collectively, these results indicate that basin-scale climatic and oceanographic variables, rather than local SST conditions may be the primary drivers for variations in the observed shifts in centennial-scale TC frequency regimes over the last 1200 y.

Methods

We present sedimentary proxy data for paleo-hurricane activity in two sediment cores from the Blue Hole of Lighthouse Reef, Belize: a short gravity core (10 cm diameter, 63 cm long), BZE-BH-GC2 (17° 18.97N, 87° 32.1W, 120 m water depth), collected with undisturbed sediment surface, and a longer vibracore (7.5 cm diameter, 532 cm long) BZE-BH-SVC4 (17° 18.97N, 87° 32.1W, 120 m water depth) that was collected using a Rossfelder® P-3 system. Whole cores were returned to Memorial University of Newfoundland for analysis, where they were first measured for bulk density using a Geotek Multi Sensor Core Logger gamma densitometer at 0.5 cm intervals. The cores were then split and imaged using Geotek Geoscan line-scanning system at 0.05 mm resolution, with images stored in RGP BMP format.

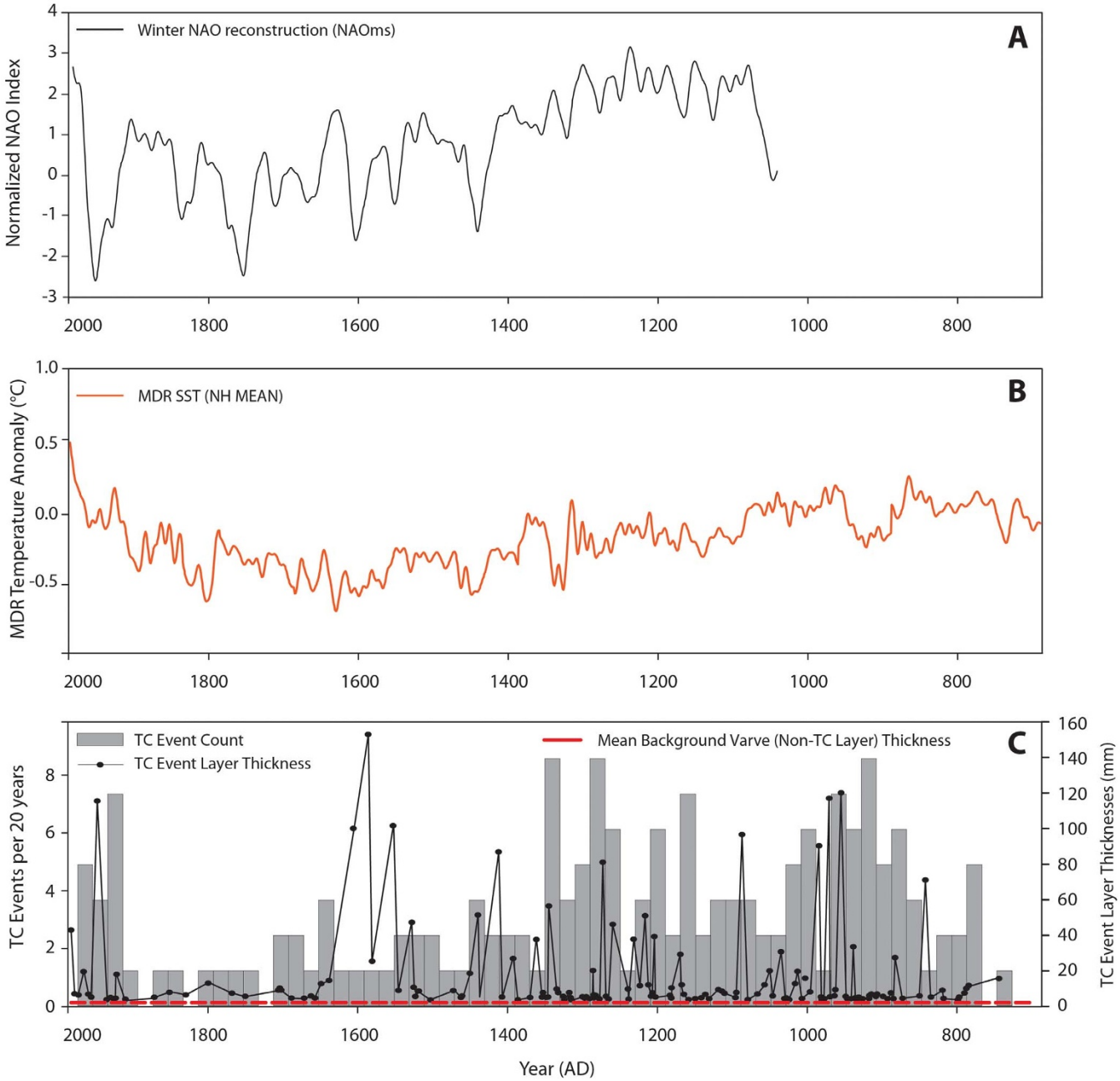

Figure 5 | TC frequency per 20 y and TC layer thickness with decadal-scale surface temperature and paleoclimate reconstructions. (A) Winter NAO reconstruction[22]; (B) MDR SST[9]; and (C) hurricane frequency per 20 y, with tropical cyclone event layer thicknesses and average background sediment varve thickness (2.5 mm).

Following Geoscan imaging, cores were subsampled for X-radiography, grain size measurement, and $^{210}Pb/^{137}Cs$ geochronological analysis. For X-radiography, axial slabs (1 cm thick) were prepared and imaged using a Thales Flashscan35 digital X-ray detector illuminated by a Lorad industrial X-ray generator. Of the density, X-radiograph, and colour-imaging data sets, the Geoscan BMP images possessed the best combination of accurate and precise spatial reference, and high spatial resolution, so those images were used for quantitative analysis of bedding thickness and depth described below.

Following the RGB image capture, Geotek ImageTools image analysis software was used to extract a horizontally averaged (20 pixels wide) RGB colour data profile along the stratigraphic axis of the core image at 0.1 mm (1 pixel) depth intervals[27]. The aperture-calibrated RGB time-series data was then converted to a greyscale/luminance (L*) time-series using the following equations:

$$(\text{Rcal, Gcal, or Bcal}) = (\text{Rraw, Graw, or Braw}) \times (\text{IA2/CA2}) \quad (1)$$

where: IA is the aperture setting used for core image capture, and CA is the aperture setting used for light and dark field calibration

$$L^* = 0.30\text{Rcal} + 0.59\text{Gcal} + 0.11\text{Bcal} \quad (2)$$

where: L* is calibrated greyscale/luminance[28].

In the case of laminated core material, layer boundaries correspond to the inflection points of the greyscale luminance curves. Our method, like other established laminae detection methods uses a differential filter for edge detection[29]. In terms of core material, the filter determines the depth-referenced contact between light and dark laminae. To implement the filter, a simple Matlab program was developed to produce a laminae count, core depth of contacts, and individual bed/lamina thicknesses. Images and data generated by the automated analysis were then compared manually to correct for errors in automated analysis associated with thick, coarse-grained beds, and artefacts from core collection and processing.

For gravity core BZE-BH-GC2 (0–62.5 cm), sub-samples for grain-size analysis and $^{210}Pb/^{137}Cs$ radioisotope geochronology were taken at relatively coarse (0.5 cm) intervals to ensure that there was sufficient material for all necessary analyses along the entire length of the gravity core (63 cm). For granulometric analysis samples were dispersed in 0.05% sodium metaphosphate solution, subsequently disaggregated in an ultrasonic bath, and then analysed using a Horiba LA-950 PARTICA particle size

analyser. Grain size was estimated visually along the entire length of the vibracore BZE-BH-SVC4 (to a maximum depth in core of 532 cm). Activities of excess ^{210}Pb and ^{137}Cs (Becquerels/g or Bq/g) were determined by γ-spectroscopy analysis of dried sediment (46.5 KeV peak for ^{210}Pb and 661 KeV peak for ^{137}Cs)[30]. Cesium-137 was not detectable at activities above 3 Bq/g. Additionally, ten Accelerator Mass Spectrometry (AMS) ^{14}C ages from organic residue samples were obtained (sample preparation performed by the Université Laval and analysis at University of California, Irvine) from the core BZE-BH-SVC4 in order to constrain the age model. Organic residue was separated from the bulk sediment material by dissolving the carbonate with HCl, washing the sample with NaOH, and repeating until no more carbonate material remained. These ages were calibrated using the Intcal09 and Marine09 curves[31] and the OxCal program[32,33]. As no site-specific ΔR value is available for the Belize Atoll system, a global marine reservoir age of 405 y was used to calibrate these ^{14}C ages. A further calibration step was undertaken by a regression between known varve age and depth with calibrated radiocarbon age, allowing development of the age model referenced to year of collection (2009) in Fig. 2.

1. Emanuel, K. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436**, 686–688 (2005).
2. Knutson, T. R. *et al*. Tropical cyclones and climate change. *Nature Geosci* **3**, 157–163 (2010).
3. Emanuel, K. Global Warming Effects on US Hurricane Damage. *Weather Clim Soc* **3**, 261–268 (2011).
4. Gray, W. M. Atlantic Seasonal Hurricane Frequency 1. El-Nino and 30-Mb Quasi-Biennial Oscillation Influences. *Mon Weather Rev* **112**, 1649–1668 (1984).
5. Shapiro, L. J. Month-to-Month Variability of the Atlantic Tropical Circulation and Its Relationship to Tropical Storm Formation. *Mon Weather Rev* **115**, 2598–2614 (1987).
6. Landsea, C. W., Pielke, R. A., Mestas-Nunez, A. & Knaff, J. A. Atlantic basin hurricanes: Indices of climatic changes. *Climatic Change* **42**, 89–129 (1999).
7. Pielke, R. A. & Landsea, C. N. La Nina, El Nino, and Atlantic hurricane damages in the United States. *B Am Meteorol Soc* **80**, 2027–2033 (1999).
8. Gischler, E., Shinn, E. A., Oschmann, W., Fiebig, J. & Buster, N. A. A 1500-Year Holocene Caribbean Climate Archive from the Blue Hole, Lighthouse Reef, Belize. *J Coastal Res* **24**, 1495–1505 (2008).
9. Mann, M. E., Woodruff, J. D., Donnelly, J. P. & Zhang, Z. H. Atlantic hurricanes and climate over the past 1,500 years. *Nature* **460**, 880–U115 (2009).
10. McCloskey, T. A. & Liu, K. B. A 7000 year record of paleohurricane activity from a coastal wetland in Belize. *Holocene* **23**, 278–291 (2013).
11. Landsea, C. N., Franklin, J. & Beven, J. *Atlantic Hurricane Database HURDAT2.* Web. <http://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html> Accessed 20 October 2013.
12. Zaibo, N., Pelinovsky, E., Kurkin, A. & Kozelkov, A. Estimation of Far-Field Tsunami Potential for the Caribbean Coast Based on Numerical Simulation. *Science of Tsunami Hazards* **21**, 202–222 (2003).
13. Lamb, H. H. The Early Medieval Warm Epoch and its Equal. *Palaeogeogr Palaeocl* **1**, 13–37 (1965).
14. Bradley, R. S. & Jonest, P. D. 'Little Ice Age' summer temperature variations: their nature and relevance to recent global warming trends. *The Holocene* **3**, 367–376 (1993).
15. Wright, L. D. [Sediment Suspension and Transport on the Inner Continental Shelf] *Morphodynamics of inner continental shelves.* [Kennish, M. J. & Lutz, P. L. (eds.)] [139–171] (CRC Press, Boca Raton, 1995).
16. Dietrich, W. E. Settling velocity of natural particles. *Water Resour Res* **18**, 1615–1626 (1982).
17. Soulsby, R. [Bedload Transport] *Dynamics of marine sands.* [159–170] (T. Telford, London, 1997).
18. Gischler, E., Anselmetti, F. S. & Shinn, E. A. Seismic stratigraphy of the Blue Hole (Lighthouse Reef, Belize), a late Holocene climate and storm archive. *Marine Geology* **344**, 155–162 (2013).
19. Elsner, J. B., Murnane, R. J. & Jagger, T. H. Forecasting US hurricanes 6 months in advance. *Geophys Res Lett* **33** (2006).
20. Elsner, J. B., Jagger, T. & Niu, X.-F. Changes in the rates of North Atlantic major hurricane activity during the 20th century. *Geophys Res Lett* **27**, 1743–1746 (2000).
21. Goldenberg, S. B., Landsea, C. W., Mestas-Nunez, A. M. & Gray, W. M. The recent increase in Atlantic hurricane activity: Causes and implications. *Science* **293**, 474–479 (2001).
22. Trouet, V. *et al*. Persistent Positive North Atlantic Oscillation Mode Dominated the Medieval Climate Anomaly. *Science* **324**, 78–80 (2009).
23. Besonen, M. R., Bradley, R. S., Mudelsee, M., Abbott, M. B. & Francus, P. A 1,000-year, annually-resolved record of hurricane activity from Boston, Massachusetts. *Geophys Res Lett* **35**, L14705 (2008).
24. Woodruff, J. D., Donnelly, J. P., Mohrig, D. & Geyer, W. R. Reconstructing relative flooding intensities responsible for hurricane-induced deposits from Laguna Playa Grande, Vieques, Puerto Rico. *Geology* **36**, 391–394 (2008).
25. Lane, P., Donnelly, J. P., Woodruff, J. D. & Hawkes, A. D. A decadally-resolved paleohurricane record archived in the late Holocene sediments of a Florida sinkhole. *Marine Geology* **287**, 14–30 (2011).
26. Toomey, M. R., Curry, W. B., Donnelly, J. P. & van Hengstum, P. J. Reconstructing 7000 years of North Atlantic hurricane variability using deep-sea sediment cores from the western Great Bahama Bank. *Paleoceanography* **28**, 31–41 (2013).
27. Nederbragt, A. & Thurow, J. in *Image Analysis, Sediments and Paleoenvironments* Vol. **7**, *Developments in Paleoenvironmental Research* (ed Pierre, Francus) Ch. **6**, 105–124 (Springer Netherlands, 2005).
28. Schneider, C. A., Rasband, W. S. & Eliceiri, K. W. NIH Image to ImageJ: 25 years of image analysis. *Nature Methods* **9**, 671–675 (2012).
29. Cooper, M. C. The use of digital image analysis in the study of laminated sediments. *Journal of Paleolimnology* **19**, 33–40 (1998).
30. Cutshall, N. H., Larsen, I. L. & Olsen, C. R. Direct Analysis of Pb-210 in Sediment Samples - Self-Absorption Corrections. *Nucl Instrum Methods* **206**, 309–312 (1983).
31. Reimer, P. J. *et al*. Intcal09 and Marine09 Radiocarbon Age Calibration Curves, 0–50,000 Years Cal Bp. *Radiocarbon* **51**, 1111–1150 (2009).
32. Ramsey, C. B. Development of the Radiocarbon calibration program OxCal. *Radiocarbon* **43**, 355–363 (2001).
33. Ramsey, C. B. Bayesian Analysis of Radiocarbon Dates. *Radiocarbon* **51**, 337–360 (2009).
34. Nittrouer, C. A. & Sternberg, R. W. The Formation of Sedimentary Strata in an Allochthonous Shelf Environment - the Washington Continental-Shelf. *Marine Geology* **42**, 201–232 (1981).

Acknowledgments

The authors acknowledge financial support from the Inter-American Institute for Global Change Research CRN2 050 grant (S.J.B.), Total S.A. (A.W.D.), the LSU Foundation (S.J.B. and K.C.D.), Geological Society of America and the Society for Sedimentary Geology (K.C.D.). The authors thank Drs. Brian Menounos (K.C.D.) and Scott Lamoureux for the use of their vibracoring system, Mr. Mario Guerrero (Belize City, Belize) for boat and logistical support, the Belize Audubon Society and Mr. James Azueta of the Belize Fisheries Department for site access, Dr. Dario Harazim for laboratory assistance, and Dr. Raymond Bradley for suggestions that improved the manuscript.

Author contributions

K.C.D., S.J.B. and A.W.D. wrote the main manuscript. K.C.D. prepared all figures and tables. All authors reviewed the manuscript.

Additional information

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Denommee, K.C., Bentley, S.J. & Droxler, A.W. Climatic controls on hurricane patterns: a 1200-y near-annual record from Lighthouse Reef, Belize. *Sci. Rep.* **4**, 3876; DOI:10.1038/srep03876 (2014).