Reconstructing 7000 years of North Atlantic hurricane variability using deep-sea sediment cores from the western Great Bahama Bank

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[1] Available overwash records from coastal barrier systems document significant variability in North Atlantic hurricane activity during the late Holocene. The same climate forcings that may have controlled cyclone activity over this interval (e.g., the West African Monsoon, El Niño–Southern Oscillation (ENSO)) show abrupt changes around 6000 yrs B.P., but most coastal sedimentary records do not span this time period. Establishing longer records is essential for understanding mid-Holocene patterns of storminess and their climatic drivers, which will lead to better forecasting of how climate change over the next century may affect tropical cyclone frequency and intensity. Storms are thought to be an important mechanism for transporting coarse sediment from shallow carbonate platforms to the deep-sea, and bank-edge sediments may offer an unexplored archive of long-term hurricane activity. Here, we develop this new approach, reconstructing more than 7000 years of North Atlantic hurricane variability using coarse-grained deposits in sediment cores from the leeward margin of the Great Bahama Bank. High energy event layers within the resulting archive are (1) broadly correlated throughout an offbank transect of multi-cores, (2) closely matched with historic hurricane events, and (3) synchronous with previous intervals of heightened North Atlantic hurricane activity in overwash reconstructions from Puerto Rico and elsewhere in the Bahamas. Lower storm frequency prior to 4400 yrs B.P. in our records suggests that precession and increased NH summer insolation may have greatly limited hurricane potential intensity, outweighing weakened ENSO and a stronger West African Monsoon—factors thought to be favorable for hurricane development.

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1. Introduction

[2] Hurricanes are natural heat engines, converting the potential energy stored in the surface ocean into wind. The efficiency of this engine is largely controlled by the oceanographic and atmospheric conditions in which the storm is forming and through which it translates. Instrumental observations suggest that the life cycle (genesis, intensity, and track) of a hurricane is influenced by a few key climate systems: the El Niño–Southern Oscillation (ENSO) [*Gray*, 1984], the West African Monsoon [*Bell and Chelliah*, 2006], solar variability [*Cohen and Sweetser*, 1975], sea surface temperatures [*Emanuel*, 2005; *Webster et al*., 2005], volcanic aerosols [*Elsner and Kara*, 1999], and the Atlantic multi-decadel oscillation [*Goldenberg et al*., 2001]. Yet, given the short length of reliable instrumental records (>1850 A.D.), the extent to which these climatic forcings influence or even dominate hurricane behavior on geologic timescales remains poorly known.

[3] Many techniques have been developed to extend records of hurricane frequency using natural archives [*Frappier et al*., 2007; *Hetzinger et al*., 2008; *Lawrence*, 1998; *Miller et al*., 2006]. Some of the most successful proxies have made use of the capacity for storms to transport allochthonous sediment to coastal depositional basins [*Donnelly and Woodruff*, 2007; *Donnelly et al*., 2001; *Lane et al*., 2010; *Liu and Fearn*, 1993; *Nott and Hayne*, 2001; *Park*, 2012]. Barrier beach material overwashed into coastal lakes and marshes has proven a particularly effective proxy for developing continuous, multi-millennial records of hurricane activity because beach and nearshore material can be easily identified within pond or marsh sequences.

[4] Reconstruction of past hurricane frequency using overwash deposits documents substantial variability in tropical cyclone activity during the past 5500 yrs B.P. [*Donnelly and Woodruff*, 2007]. These studies have suggested a

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pervasive influence of ENSO and the West African Monsoon in pacing Atlantic hurricane frequency over the late Holocene. Mechanistically, El Niño is thought to cause increased vertical shear in the main development region limiting hurricane development [*Gray*, 1984]. Likewise, drought over the Sahel is associated with a weaker easterly wave, stronger vertical shear and, in turn, lower hurricane frequency [*Goldenberg and Shapiro*, 1996; *Gray and Landsea*, 1992].

[5] Modeling efforts indicate that long-term changes in solar insolation may also have played a key role in determining the Holocene hurricane activity. *Korty et al*. [2012] suggest that precession-forced increases in northern hemisphere summer insolation and atmospheric temperature around 6000 yrs B.P. may have limited hurricane potential intensity. However, the variable sensitivity of back-barrier sites to sea-level changes has hampered efforts to confidently develop mid-Holocene storm records and test this hypothesized forcing. Alternatively, sedimentation along carbonate bank margins has been shown to be relatively continuous over the past 7000 years [*Grammer and Ginsburg*, 1992; *Roth and Reijmer*, 2004; *Wilber et al*., 1990] and considerably less influenced by Holocene sea-level changes in comparison to coastal environments. As a result, these sediment records offer an unexplored archive of long-term tropical cyclone activity.

[6] Storms are thought to be important mechanisms for transporting carbonate bank sediments to the deep sea. *Pilskaln et al*. [1989] deployed sediment traps (500 mbsl) in the Providence Channel, the Bahamas, and found that fair-weather sedimentation was low in bank carbonates, the main component of the underlying sediments. To balance this discrepancy, they argue that storms are the key mechanism driving offbank transport. Elsewhere, sediment traps (500, 1500, 3200 m) deployed 75 km offshore of Bermuda captured this process during the passage of Hurricane Fabian in 2003 [*Weber et al*., 2006] and Ivan in 2010 (M. Conte, personal communication). At the Ocean Flux Program site, fallout of re-suspended platform material from these storms resulted in the largest observed sediment fluxes to date.

[7] Storms are likely even more important for mobilizing coarse bank-top sediments and moving them offbank. Working in the Northern Bahamas, *Hine et al*. [1981] found that under fair-weather conditions, tidal- and wind-generated currents were insufficient to mobilize sand and build observed sand waves. Even with gusts up to 20 knots, *Grammer and Ginsburg* [1992] did not observe transport of sand from the bank into the Tongue of the Ocean (Bahamas). Along the northern, open margin of St. Croix, the passage of Hurricane Hugo in 1989 removed 2 million kilograms of sand from the Salt River Submarine Canyon, the equivalent to a century of fair-weather conditions [*Hubbard*, 1992]. Together, these studies suggest that storms may periodically mobilize coarse bank-top sediments, deposit them offshore, and provide a long-term sedimentary record for hurricane activity.

[8] Unlike conventional back-barrier settings, sedimentary archives from carbonate bank margins likely extend into the early Holocene [*Lynch-Stieglitz et al*., 2009; *Roth and Reijmer*, 2004] and such sites are widespread in the tropics. These sites also offer the advantage of having high sedimentation rates (SR) while being accessible to large ocean-going research vessels capable of recovering such expanded sequences. While working on carbonate bank sediments also offers several obstacles (i.e. isolating the effects of local geomorphology, gravity flows, winnowing from currents, changes from fringing reefs to an open margin conditions on the banktop, deposition from tsunamis), these confounding effects can be overcome through careful site selection and thoughtful experimental design (see Methods section).

[9] Here, we use a suite of cores from the Leeward Great Bahama Bank to address three main questions: (1) Is it possible to reconstruct long-term hurricane records using cores from carbonate bank margins? (2) How has tropical cyclone activity around the Bahamas changed over the Holocene? (3) Does the record of hurricane strikes from the Bahamas support a relationship between ENSO, West African Monsoon or solar insolation, and storminess during the early Holocene?

2. Study Site

[10] Located in the Northeastern Caribbean, the Great Bahama Bank is optimally positioned to test this new approach for reconstructing past hurricane activity (Figure 1). Sedimentary records from the Bahamas and specifically at our site have been well studied, providing an established geologic context in which to test our proxy. Earlier work shows that offbank transport has led to rapid progradation of the leeward margin of the Great Bahama Bank during this and previous interglacial periods [*Eberli et al*., 1997]. Substantial areas along the modern platform margin (100–10 mbsl) were progressively flooded during deglaciation, initiating carbonate production before subsequent transport and deposition of this material offshore. The main phase of platform flooding was completed around 7000 yrs B.P. [*Grammer and Ginsburg*, 1992; *Roth and Reijmer*, 2004; *Wilber et al*., 1990], greatly enhancing the accumulation rates along the leeward margin.

[11] Previous work at our site documents a series of Holocene depositional environments moving from the banktop into the Straits of Florida [*Rendle and Reijmer*, 2002; *Wilber et al*., 1990]. We divide site geometry into five zones on the basis of slope and deposition rate (Figure 1c): (1) platform, (2) bank-edge depocenter: 10–100 mbsl, (3) upper slope: 100–250 mbsl, (4) mid-slope: 250–400 mbsl, and (5) lower slope: 400–700 mbsl. The platform itself (~0 to 10 mbsl) stretches 65 km west from the Andros Island (Figure 1b) before gradually transitioning to a shallowly oceanward dipping margin. Seismic surveys [*Wilber et al*., 1990] indicate that over the Holocene, up to 15 m of sediment has accumulated along the bank edge (3 km wide), gradually decreasing the slope since flooding. The shelf break (~100 mbsl) marks a shift to steeper slopes (0.1 to 0.15) and an area of low deposition. Sedimentation rates increase substantially on the upper slope (>250 mbsl) with a large Holocene accretionary wedge, upwards of 50 m thick [*Wilber et al*., 1990] grading into the Straits of Florida [*Ryan et al*., 2009]. Morphologically, the lower slope (~400–700 mbsl) is characterized by a network of wide, shallow gullies that distribute material moving offbank [*Mulder et al*., 2012]. However, comparison of ridge and gully deposition using cores taken from the Northwest Providence Channel, Bahamas, indicates that there is little difference in ongoing sedimentation between sites and that channel features may be relict from earlier glacial cycles [*Burns and Neumann*, 1987]. Earlier work [*Lund and Curry*, 2006, *Lynch-Stieglitz et al*., 2009; *Lund et al*., 2006; *Lynch-Stieglitz et al*., 2011]

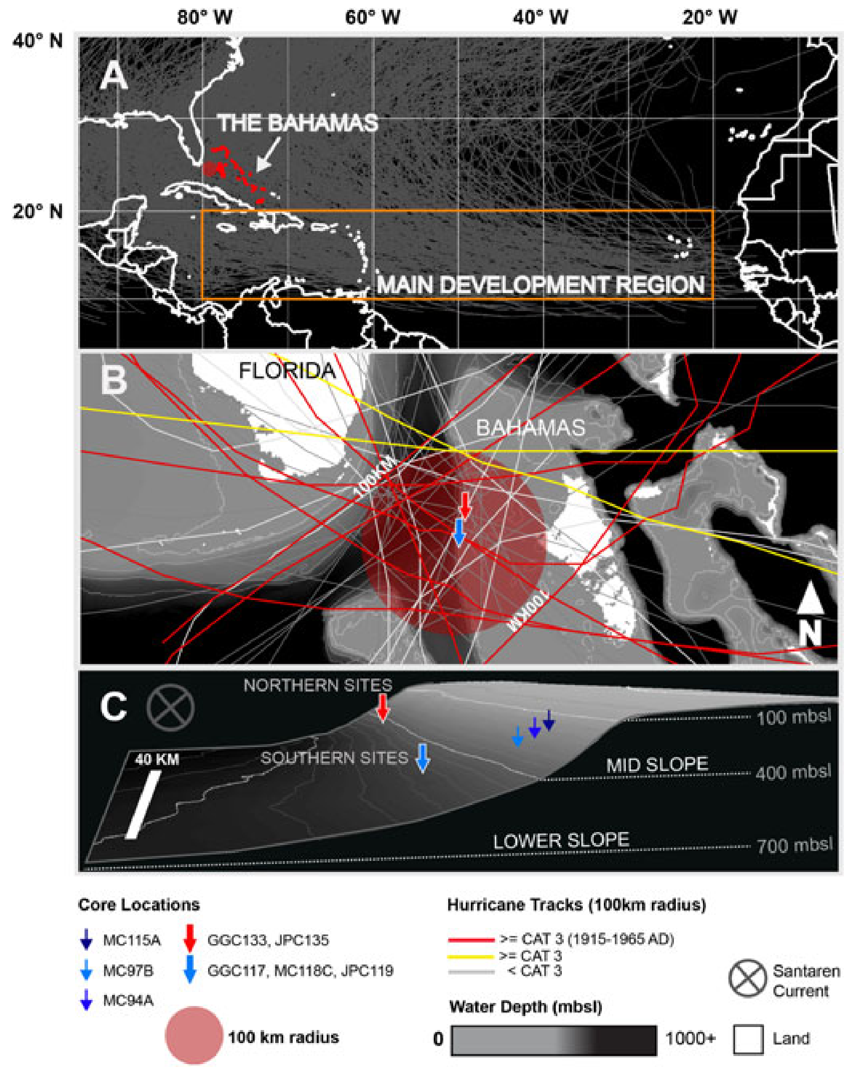

Figure 1. (a) Map showing North Atlantic Hurricanes since 1851 A.D. Blue circle shows the location of cores used in this study. Grey lines show the track of storms from the IBTRaCS dataset [*Knapp et al.* 2010]. The main development region is outlined in orange. (b) Bathymetric map of the western Great Bahama Bank and storm tracks passing near our site. Tracks of major hurricanes passing within 100 km of our site between 1915 and 1965 are shown by red lines. The two major hurricanes that passed near our site that did not occur during this interval (1888 and 1992 A.D.) are shown by yellow lines. Minor hurricanes/storms passing within that radius are highlighted in light grey lines. (c) 3D image showing general bank morphology at our site.

on the cores used in this study documented more than 12 m of Holocene sediment with relatively constant sedimentation rates since 7000 yrs B.P. at our site.

[12] Instrumental observations (IBTRaCS; http://www.ncdc.noaa.gov/oa/ibtracs/) show that the Bahamas lie along a major storm track and that our site has been hit many times since 1851 A.D. [*Knapp et al.* 2010]. Over this interval, 45 storms (≥tropical depression) have passed nearby (<100km) our sites (Figure 1). Twelve of these storms were at major hurricane strength (≥CAT 3, 86 knots 10 min sustained winds) within a 100 km radius of our core locations. The pattern of hurricane strikes near the Great Bahama Bank appears consistent with peaks in basin-wide storm frequency seen between 1920 and 1970 AD. A substantial increase in intense storms near our site in the Bahamas occurs between 1915 and 1965 A.D. with 10 of 12 major hurricanes occurring over this interval. The two storms (>CAT 3) not occurring over this interval (1888 and 1992 A.D.) also track somewhat further North than the other major hurricanes passing near our site during the historic interval. Together with several nearby overwash reconstructions [*Donnelly and Woodruff*, 2007; *Park*, 2012; *van Hengstum et al.*, 2013] these known hurricane strikes provide an opportunity to calibrate our storm record.

3. Materials and Methods

[13] The methods for this study were intended to accomplish two objectives: (1) to use a depth transect (Table 1) of multi-cores across the slope (KNR 166-2 MC 115A: 202 mbsl, MC 94A: 259 mbsl, MC 97B: 303 mbsl, MC 118C: 531 mbsl) to establish sedimentation patterns during fair-weather versus storms, and control for changes in the

Table 1. Core Locations and Water Depths[a]

Sites	Latitude (°N)	Longitude (°W)	Water Depth (m)	Modeled Timespan
Northern Sites				
KNR166-2 GGC 133	24.8360	79.2185	445	0 to 1500 yrs BP
KNR166-2 JPC 135	24.8358	79.2187	446	200 to 9500 yrs BP
Southern Sites				
KNR166-2 MC 94A	24.5687	79.2255	259	−50 to 280 yrs BP
KNR166-2 MC 97B	24.5640	79.2295	303	−50 to 165 yrs BP
KNR166-2 MC 115A	24.5712	79.2213	202	−50 to 140 yrs BP
KNR166-2 GGC 117	24.5907	79.2687	528	330 to 2400 yrs BP
KNR166-2 MC 118C	24.5906	79.2687	531	−50 to 750 yrs BP
KNR166-2 JPC 119	24.5905	79.2687	529	200 to 10250 yrs BP

geomorphological environments encountered moving off-bank, and (2) to use a 40 km, along-bank transect of gravity and jumbo piston cores (JPC 119: 529 mbsl, JPC 135: 446 mbsl) to establish a coherent pattern of storm-related sedimentation since the early Holocene and isolate the effects from local gravity flows.

[14] Each of the multi-cores was continuously sampled at 0.5 cm resolution and wet sieved at 63 μm. At the same time, a sample was taken every 0.25 cm for analysis using a Beckman-Coulter laser particle size analyzer. Based on this analysis, we calculated the standard deviation of the grain size distribution (sorting) and used it to assess the impact of winnowing from the Florida/Santaren Currents. Similar laser particle size (LPS) methods were used for the piston and gravity cores but with sampling resolutions of 1 and 0.5 cm, respectively. Comparison of these records to nearby overwash reconstructions at sites with various orientations to the sea was used to rule out tsunamis as a main driver of off-bank transport. The coarse sediment retained after the bulk samples were sieved at 63 μm was also qualitatively inspected under a stereo microscope to explore downcore changes in faunal assemblages and control for shifts in sediment composition on the bank-top. We used an ITRAX core scanning XRF to radiograph each of the multicores and identify potential sedimentary structures.

[15] The cores were chronologically constrained with both ^{210}Pb and radiocarbon dating. ^{210}Pb dating was used to establish a high-resolution chronology in the coretop so our record could be compared to storm histories for the Bahamas. After the bulk sediment was sampled from the core, dried, and homogenized using a mortar and pestle, ^{210}Pb activity was measured using gamma spectroscopy [e.g., *Gäggeler et al*., 1976]. In general, we interpreted a ^{210}Pb profile (Figure 2a, black line) based on the observed activity (Figure 2a, red dots) and used a constant initial concentration model (CIC) to extract a sedimentation rate over the past 150 years [*Appleby and Oldfield*, 1978; *Appleby and Oldfieldz*, 1983]. Radiocarbon dating of mixed planktonic foraminifera (Table 2) was used to supplement the previously established chronologies for these cores [*Lund and Curry*, 2006; *Lund et al*., 2006; *Lynch-Stieglitz et al*., 2009; *Lynch-Stieglitz et al*., 2011]. Analysis was performed at the National Ocean Sciences Accelerator Mass Spectrometry facility in Woods Hole, Massachusetts. Dates were calibrated using CALIB 6.0 and a standard marine reservoir correction of 400 years. Linear interpolation was used to set the chronology between time points.

[16] Spectral amplitudes and significance were calculated using REDFIT [*Schulz and Mudelsee*, 2002]. Unlike conventional spectral techniques, REDFIT directly computes spectral amplitudes using the Lomb-Scargle Fourier transform [*Lomb*, 1976; *Scargle*, 1982], therefore avoiding errors introduced through interpolation of uniform time spacing. Significant peaks were evaluated against a red noise background and bias corrected using 2000 Monte-Carlo simulations.

4. Results and Discussion

4.1. Multicore ^{210}Pb Chronologies and Grain-size

[17] A matrix of fine-grained carbonate mud (median grain-size ~20 μm) and aragonite needles was the primary sedimentary constituent in the cores, which in turn provides matrix support to coarse-grained biogenic grains (e.g., benthic and planktic foraminifera, halimeda, and shell fragments) and few carbonate clasts. These sediments typify deposition on the slope of the Bahamian carbonate banks during Neogene sea-level highstands [*Bernet et al*., 2000]. In general, fine-grained carbonate mud with some coarse biogenic material represents background sedimentation, whereas the proportion of coarse-grained biogenic material increases during transport events [*Bernet et al*., 2000].

[18] On a more detailed level, neither visual inspection nor x-radiography could reveal any sedimentary structures in the cores. Further detailed analysis of the textural changes, however, revealed synchronous variation in the quantity of coarse material (percent sand in μm) deposited at the core sites (Figure 2). This coarse material is primarily biogenic and dominated by both benthic and planktic foraminifera. Benthic foraminifera included shallow platform-derived species such as miliolids (e.g., *Quinqueloculina*, *Triloculina*) and taxa employing photosymbionts (e.g., *Amphistegina*, *Arachaias*), as well as rotaliids. Foraminifera also dominate the coarse-grained sediments deposited by turbidites along the western margin of the Great Bahama Bank during the Neogene; however, these carbonate turbidites generally exceeded 25 cm in thickness [*Bernet et al*., 2000]. In contrast, we observed discrete variability and peaks in coarse-grained sedimentation at centimeter scale. These results indicate that the recovered sequences most likely contain an alternation between background fine-grained sedimentation versus event layers containing relatively more coarse-grained material derived from the bank top or biogenic sediment concentrated during offshore transport.

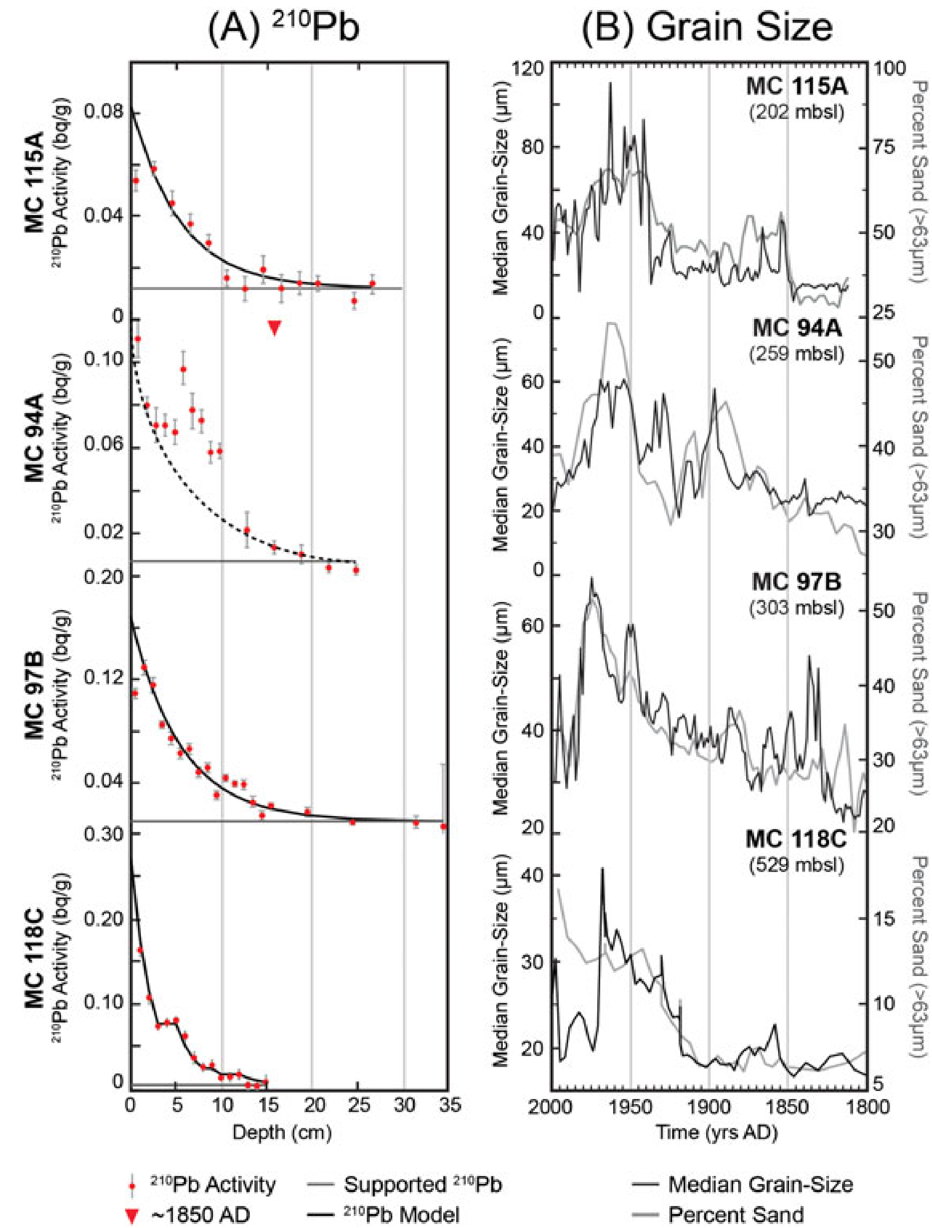

Figure 2. (a) ^{210}Pb profiles and age models for same multi-core transect. Measured ^{210}Pb activity is given by red circles. Supported ^{210}Pb is shown as light grey line. Inferred ^{210}Pb model is shown in black curves. For MC 94A, a black dashed line is used to show that the ^{210}Pb chronology is likely made more complex by erosion and re-deposition. Approximate depth of 1850 A.D. in MC 94A determined by ^{210}Pb is marked by red triangle. (b) d50 grain-size (black line) and percent sand (>63 μm; grey line) are shown for our offbank series of multicores (top: KNR 166-2 MC 115A; MC 94A; MC 97B; bottom: MC 118C).

[19] On the broad scale, ^{210}Pb activity declines almost exponentially downcore at each of our multi-core sites, largely conforming to the expectations of our CIC model with steady accumulation rates (Figure 2). However, coretop ^{210}Pb activity does increase with increasing offshore distance from the Great Bahama Bank (MC115A = 0.08 bq/g; MC118C = 0.25 bq/g), possibly indicating that certain banktop constituents or grain-size fractions contain slightly different initial concentrations ^{210}Pb.

[20] ^{210}Pb profiles along our depth transect reflect different sedimentation rates across the slope (Figure 2) and fall within three depositional zones (Figure 1c): variable deposition and erosion (upper slope); continuous deposition (mid-slope) and event deposition (lower slope) with gradual background sedimentation. SR at sites on the upper slope (MC115A SR = 1.6mm/yr; 94A SR = 1.0mm/yr) appear more variable, with higher accumulation rates coinciding with deposition of coarse material. This suggests that deposition may be driven by hurricane events, and that under fair weather conditions, most material bypasses the upper slope. The divergence of MC 94A's ^{210}Pb profile from the expected curve may indicate that a more complicated mix of deposition and erosion is occurring on the upper slope. Higher accumulation rates and continuous deposition occurs

Table 2. Radiocarbon Dates for Cores Used in This Study[a]

Site	Depth (cm)	Species	^{14}C Age (yrs BP)	^{14}C Error (years)	Cal Age (yrs BP)
KNR166-2 GGC 117	31.0	*G. ruber*	1090	30	649
	61.0	*G. ruber*	1430	30	962
	89.0	*G. ruber*	1550	30	1101
	148.5	*G. ruber*	2330	90	1954
	205.0	*G. ruber*	2570	100	2224
KNR166-2 MCA 118	0.5	*G. ruber*	>Mod		
	13.0	*G. ruber*	635	25	281.5
	36.5	*G. ruber*	1320	45	885
KNR166-2 JPC 119	10.5	*G. sacculifer*	575	40	206
	190.5	Mixed planktonics	2190	25	1788
	440.5	Mixed planktonics	2840	30	2610
	770.5	Mixed planktonics	3870	25	3838
	1070.5	*G. sacculifer*	4960	35	5306
	1130.5	*G. sacculifer*	5270	50	5632
	1200.5	*G. sacculifer*	6190	60	6630
	1300.5	*G. sacculifer*	8710	55	9387
	1310.3	*G. sacculifer*	9420	50	10268
KNR166-2 GGC 133	0.5	*G. ruber*	>Mod		
	136.0	*G. ruber*	1570	35	1122
	267.5	*G. ruber*	1920	30	1454
KNR166-2 JPC 135	10.5	*G. sacculifer*	580	35	215
	200.5	Mixed planktonics	2050	35	1620
	510.5	Mixed planktonics	2710	30	2392
	720.5	*G. sacculifer*	3430	50	3307
	1080.5	Mixed planktonics	5450	45	5822
	1290.5	*G. sacculifer*	6800	65	7326
	1308.3	Mixed planktonics	7790	50	8260
	1322.3	*G. sacculifer*	7560	40	8016
	1328.5	*G. sacculifer*	8820	45	9484

[a]Radiocarbon chronology for MC 118C is based on dates in corresponding multi-core MC 118A.

on the mid-slope (MC 97b; 303 mbsl; SR = 1.7 mm/yr). At the toe of the slope (MC 118C; 531 mbsl, SR = 0.5mm/yr), the ^{210}Pb chronology indicates periodic deposition of event layers (1–2 cm thick) and gradual, but steady background sedimentation. The largest grain size event (3–5 cm depth) appears to have internal bedding, while the two earlier events (8–9 and10–12 cm) fine upwards. Together, the ^{210}Pb chronologies indicate that small turbidites are the likely mechanism for moving sediments offbank, and that the most continuous sedimentary records occur below the mid-slope (400 mbsl).

[21] Despite the complex sedimentary mechanics across the bathymetric and geographic transects in the framework of our ^{210}Pb chronologies, a coherent pattern of coarse layers emerges between the multi-cores and both grain-size techniques (i.e., sieving or LPS). Grain-size patterns in our multicore transect (200–530 mbsl) are similar and do not appear greatly affected by changes in geomorphology moving downslope, in particular channelization below 400 mbsl [*Mulder et al*., 2012]. Together, they show a substantial rise in coarse-grained deposition after 1915 A.D. from several discrete events (Figure 3). The coarsest peaks match well with a documented period of increased major storm frequency (10 CAT 3+ hurricanes) near the Bahamas between 1915 and 1965 A.D. The three thickest coarse layers (3–5, 8–9, and 10–12 cm) in our records occur around 1920, 1930. and 1965 A.D., possibly reflecting deposition during Hurricane Betsy (1965 A.D., CAT 3) and two unnamed category 4 storms which hit the Bahamas in 1919 and 1929 A.D. However, given historic return intervals (~3 years) and sedimentation rates at our sites (0.5–1.7 mm/yr), most peaks likely reflect increased hurricane activity on decadal

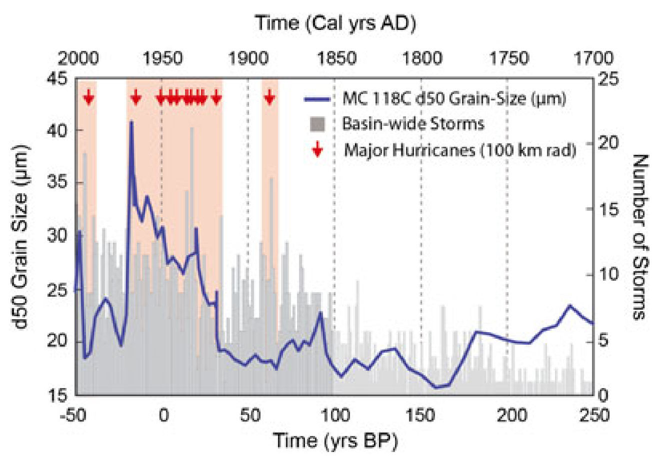

Figure 3. Comparison of historic storms and bulk grain-size records. A comprehensive record of Historic North Atlantic hurricanes was compiled from HURDAT (2000–1851 A.D.), *Chenoweth* [2006], and *Scheitlin et al*., [2010] (shaded grey; 1850–1700 A.D.). Annual number of Atlantic storms (≥tropical storm) is shown by grey bars. Major hurricanes passing within 100 km of our site are highlighted by red arrows. d50 grain-size from core KNR 166-2 MC 118C is given by the blue line.

timescales rather than individual storms. Two periods of very low coarse grain deposition occur from 1875 to 1915 A.D. and 1965 to 1990 A.D., and are consistent with observed decreases in major hurricane frequency in historic records for the Bahamas. The lower frequency of documented storms recorded prior to 1850 A.D. may reflect that fewer ships were crossing the Atlantic at this time and many storms not making landfall were missed.

[22] Overall, this pattern suggests a close link between major storms and coarse sediment deposition; however, the exact size of individual layers is likely impacted by several factors: (1) storm intensity, (2) approach, and (3) speed, as well as (4) sediment availability on the banktop. Storm intensity and wind speed are likely closely tied to wave processes, shear stress at the bed, and therefore the ability of a storm to mobilize and transport coarse sediment [*Chang et al.*, 2001]. In general, more intense storms with stronger winds are likely able to transport coarser sediment. Storm approach is also likely to play a key role in determining if sediment, once mobilized, is moved offbank. In general, major storms have tracked east-west across the Bahamas (Figure 1). Because of the cyclonic orientation of storm winds, hurricanes tracking north of our site will build up water on the platform. Upon release, this water will flow offbank, eroding sediment along the platform edge [*Hubbard*, 1992]. Alternatively, storms passing to the south of our site have their strongest winds oriented offbank. A direct strike may result in little offbank transport as the peak winds will be oriented along bank (north-south). In addition, the speed of the storm will limit the time hurricane winds have to deliver material offbank. Slower moving storms may clear most of the fine sediment offbank early on, leaving only coarse sediment to be mobilized and redeposited offbank later in the event. Likewise, passage of many large storms over a relatively short interval may deplete banktop fines, leading to progressively coarser deposits. Deployment of sediment traps to capture this process is necessary to better constrain each of these influences.

[23] On the basis of our analysis and in light of previous efforts, we do not believe that these deposits were formed either by the passage of winter storm fronts or winnowing. Density cascading during the passage of winter storms has been shown to be significant in transporting fine mud off platform [*Wilson and Roberts*, 1995], but these flows are likely low in coarse silt and sand [*Neumann and Land*, 1975]. Coarse deposits are also not readily explained as derived from winnowing by the Florida current because, as noted above, ^{210}Pb chronologies indicate that much of the coarse sediment on the lower slope is from "instantaneous" event deposits. Moreover, coarse layers in our multi-cores do not show significantly increased sorting as would be expected from winnowing. In fact, a Pearson's product-moment test (MATLAB: corr) indicates only a weak, negative correlation ($r = -0.22$, $p < 0.01$) between grain size and sorting (standard deviation) for MC118C.

[24] Synthesis of ^{210}Pb chronologies, downslope grain-size records, and historic storm records, introduces confidence for using coarse grain deposition as a proxy for major storms or intervals of major storm activity at the study site. Our records support the hypothesis that storms cause coarse material from the bank edge to become re-suspended and carried offbank as turbidity currents. Deposition of several large (1–2 cm thick) discrete coarse-grained layers during major hurricane events during the historic interval (>1850 A.D.) indicates that the lower slope presents a good depositional setting for developing longer hurricane records.

4.2. Comparison of Event Deposition to Previous Late-Holocene Overwash Records

[25] Two pairs of gravity and piston cores (JPC 119: 529 mbsl, JPC 135: 446 mbsl) stretching 40 km along bank define a consistent pattern of high-energy event deposition (Figure 4) and define at least four periods of increased coarse fraction deposition: (1) 4600 to 3800 yrs BP; (2) 2400 to 1800 yrs BP; (3) 1200 to 500 yrs BP and (4) ~50 yrs BP to present. Given that these sites are separated by more than 40 km and that the event layers are synchronous across this transect indicates these deposits are not explained by random and localized debris flow events. Furthermore, it is improbable that mass wasting would occur, given that the maximum gradient (0.15) in the upper slope is below the angle of repose for mixed coarse-fine grained sediment [*Kenter*, 1990]. The simplest explanation for these geographically distributed and synchronous coarse, high-energy layers is storm-mediated transport.

[26] Similar increases in hurricane activity are widely documented throughout the North Atlantic between 4900 and 3600, 2500 and 1000, and 600 and 400 yrs BP, and since 1700 A.D. [*Donnelly and Woodruff*, 2007; *Liu and Fearn*, 1993; *Park*, 2012; *Scileppi and Donnelly*, 2007; *van Hengstum et al.*, 2013], consistent with our offshore results, and have previously been attributed to changes in El Niño and the West African Monsoon. These changes are observed throughout the North Atlantic in coastal locales with various geometric orientations to the ocean, which means they cannot be sufficiently explained by tsunami events. Correspondence between our records and previous Caribbean overwash records gives further confidence in interpreting older, mid-Holocene, coarse deposits in our cores as hurricane-derived.

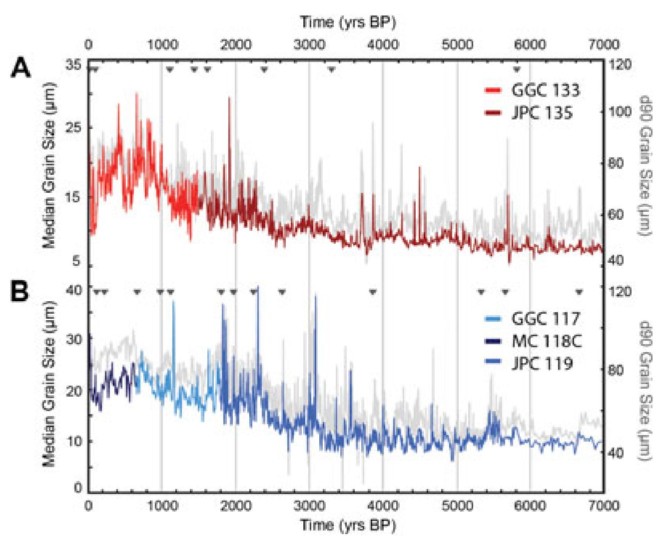

Figure 4. Storm-related changes in grain size along the Great Bahama Bank. Median (d50) grain size shown in red (northern sites) or blue (southern sites). d90 grain size shown by grey line. Grey triangles mark radiocarbon tie points. (a) Light red shows d50 grain size from KNR166-2 GGC 133, while dark red line gives the median grain-size profile for KNR 166-2 JPC 135. (b) Compiled profiles at our southern site using KNR 166-2 MC118C (dark blue), GGC117 (light blue), and JPC119 (medium blue). Modeled timespans for each core are given in Table 1.

4.3. Mid-Late Holocene Hurricane Activity

[27] These short-term peaks in storminess, likely forced by ENSO and the West African Monsoon, overlie a much broader increase in the background storm climate between 3000 to 2000 yrs BP. Prior to 4400 yr BP, storms appear infrequent and active intervals are short-lived (e.g., 5800 to 5500 yrs BP). Given our site geometry, this long term increase in coarse sedimentation is unlikely related to changing sea level or sensitivity to storms. In fact, lower sea level during the mid-Holocene would be expected to have an opposite effect, making it easier for storms to mobilize sediment from a shallower banktop and move it offshore. Relatively uniform sedimentation rates between ~6000 and 2000 yrs BP in our piston cores (JPC 119 SR = 2.4 mm/yr, JPC 135 SR = 2 mm/yr) further indicate that Holocene sea-level rise did not alter the region's sensitivity to hurricane activity. On the other hand, decreasing sedimentation rates (GGC117 SR = 1.1, GGC 133 SR = 2 mm/yr) since ~2000 yrs BP may in fact reflect increased storm frequency with hurricanes sweeping much of the fine sediment into the Straits of Florida.

4.4. Connections Between Hurricanes and Other Climate Systems

[28] Our results suggest a dynamic relationship between hurricanes and climate with different forcings playing a driving role during different parts of the Holocene (Figure 5). Major changes in storm frequency during the late Holocene appear driven mostly by an ENSO-like forcing and West African Monsoon variability, consistent with previous results [*Donnelly and Woodruff*, 2007]. However, these relationships appear to breakdown during the mid-Holocene when we observe lower hurricane activity despite a stronger West African Monsoon [*Nguetsop et al.*, 2004] and weaker El Niños [*Makou et al.*, 2010; *Moy et al.*, 2002], factors thought to enhance hurricane activity.

[29] The diminished role of El Niño in forcing North Atlantic hurricane activity during the mid-Holocene may have resulted from decreased high-frequency ENSO variability at this time [*Korty et al.*, 2012; *Moy et al.*, 2002]. *Korty et al.* [2012] suggest that the rapid shifts in atmospheric temperature experienced during ENSO events may drive large fluctuations in the ocean-atmosphere thermal gradient and therefore hurricane activity. A recent reconstruction by *Makou et al.* [2010] suggests that the magnitude of ENSO variability was substantially lower prior to 2000 yrs BP, possibly explaining the decreased mid-Holocene hurricane activity we observe in our records. Still, many current proxies used to reconstruct Holocene-scale records of ENSO do not satisfactorily reproduce observational data. More explicit, annually resolved records are needed to definitively characterize the relationship between tropical Pacific dynamics and Atlantic hurricane activity.

[30] Likewise, key differences in the behavior of the West African Monsoon and the ITCZ during the mid-Holocene may have augmented their roles in shaping North Atlantic storm activity. At present, the ITCZ's summer position promotes monsoon and hurricane development near the Sahel region of Africa (Figure 1). However, evidence of ITCZ migration from the Cariaco Basin [*Haug et al.*, 2001] indicates that its mean position may have been

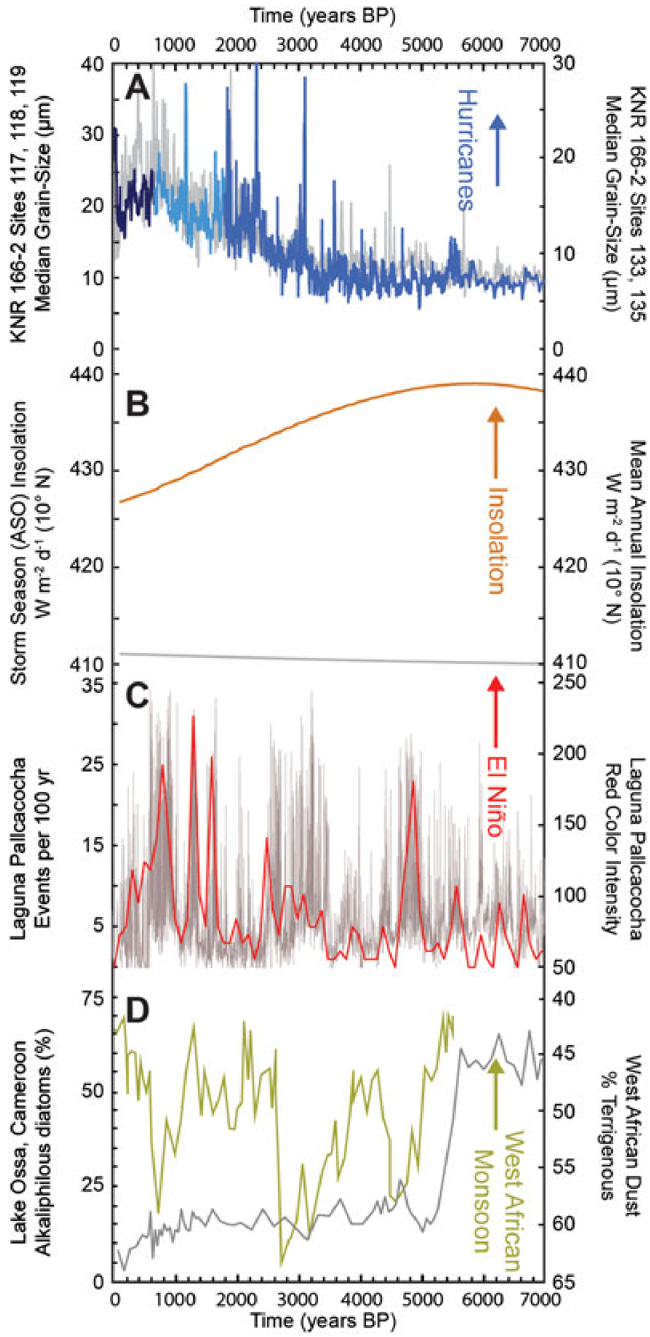

Figure 5. Comparison of the Bahamas hurricane reconstruction to records of ENSO, solar insolation, and the West African Monsoon. (a) Bahamas hurricane records from our southern sites (KNR 166-2 MC118C, GGC117, and JPC119) are shown in blue (same as Figure 4). Grain-size profiles for our northern sites (KNR 166-2 GGC133 and JPC135) are shown in grey. (b) Storm season (ASO) incoming solar insolation at 10°N (orange) and mean annual insolation at 10°N (grey) [*Huybers*, 2012 (inso.m, http://www.people.fas.harvard.edu/~phuybers/Mfiles/Toolbox/), and references therein]. (c) Laguna Pallcochoa red color intensity (grey), El Niño events per 100 years (red) [*Moy et al.*, 2002]. (d) Lake Ossa Alkaliphilous diatoms (%) (yellow) [*Nguetsop et al.*, 2004]. Terrigenous dust flux at site 658C offshore of West Africa (grey) [*deMenocal et al.*, 2000].

considerably further north during the mid-Holocene, reflecting warmer NH summers. This shift coincides with the African Humid Period and inferred increases in precipitation over North Africa [*deMenocal et al*., 2000] (Figure 5). A northward shift in hurricane genesis locations (and tracks) may have considerably diminished storm frequency in the Bahamas and possibly the ability to generate major hurricanes in the North Atlantic.

[31] Recent modeling efforts implicate increased solar radiation as a limitation to hurricane potential intensity across much of the North Atlantic during the mid-Holocene [*Korty et al*., 2012]. Increased insolation and atmospheric temperature may work to decrease the thermal gradient between the ocean and tropopause, effectively limiting potential intensity. This effect appears particularly strong between 20 and 35°N in the North Atlantic. Even today, conditions are less conducive to developing major storms at these latitudes than further south [*Korty et al*., 2012]. Together, this suggests that increased NH summer insolation combined with a northward shift in the ITCZ and main genesis location may have resulted in the observed decrease in hurricane activity around the Bahamas during the mid-Holocene.

[32] Our results also indicate that significant changes in hurricane frequency occur on much shorter timescales as well. Spectral analysis of our grain-size records reveals many significant (90%) peaks for periods between 11 and 20 years (Figure 6). Those peaks between 11 and 14 years are particularly strong. One relatively unexplored mechanism for this variability is short-term change in solar insolation. High frequency oscillations in solar radiation at 11 year periods (Schwabe cycle) are well documented in observational records [*Lockwood and Fröhlich*, 2007 and references therein]. Although changes in top of the atmosphere irradiance are relatively minor (~0.07%) over a typical 11 year solar cycle, the amplitude of this oscillation in the UV spectrum is much more substantial (~6%) [*Gray et al*., 2010]. Both ozone concentration and absorption are particularly sensitive to changes in UV radiation, both increasing substantially during solar maxima [*Gray et al*., 2010]. Coupling between the upper and lower atmospheres means that solar-induced changes in stratospheric ozone increase tropospheric temperatures [*Shindell et al*., 1999], thereby limiting hurricane potential intensity [*Elsner et al*., 2010].

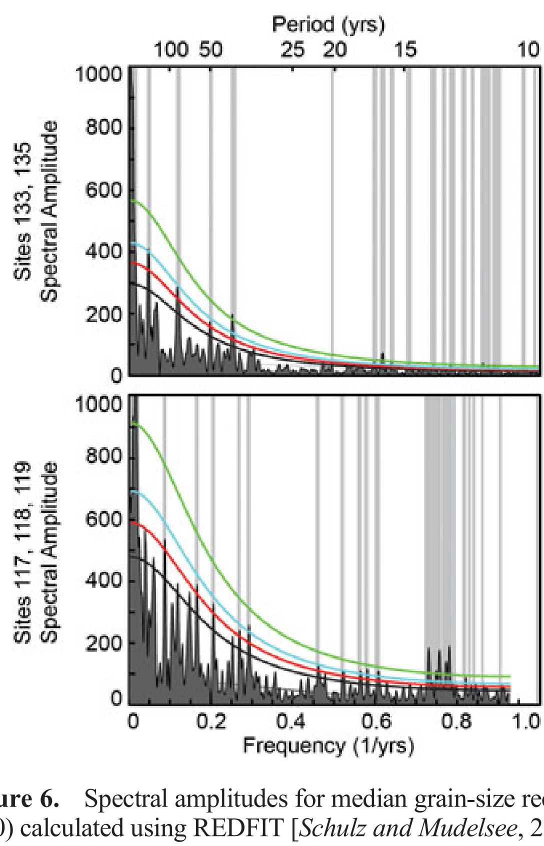

Figure 6. Spectral amplitudes for median grain-size records (d50) calculated using REDFIT [*Schulz and Mudelsee*, 2002]. Parameters are as follows: OFAC = 4, HIFAC = 1, n50 = 4, Iwin = 1. Northern sites (top). Southern sites (bottom). Spectral amplitudes shown in grey. χ^2 significance levels are shown as black (80%), red (90%), blue (95%), and green (99%). Grey bars highlight peaks exceeding a 90% χ^2 threshold.

[33] Similar periodicities have also been noted for other hurricane-forcing mechanisms, notably the Atlantic SST Dipole. Analysis of tropical Atlantic SSTs [*Chang et al*., 1997; *Enfield and Mayer*, 1997; *Houghton and Tourre*, 1992] has identified a persistent temperature dipole across the ITCZ that oscillates on decadal timescales. This is thought to impact North Atlantic hurricane activity both directly through changes in SST and indirectly by modulating the West African Monsoon [*Landsea et al*., 1999; *Xie et al*., 2005]. Indeed, it is possible that several of the high frequency variations observed in our records, and likewise in late Holocene reconstructions of the West African Monsoon [*Shanahan et al*., 2009], arise from oscillations between modes of the Atlantic SST dipole. The Atlantic multi-decadal oscillation is also thought to control Atlantic SSTs and impact the West African Monsoon, as well as hurricane activity [*Goldenberg et al*., 2001; *Knight et al*., 2006; *Zhang and Delworth*, 2006] on short timescales. However, significant controversy has surrounded the role AMO has played in modulating hurricane activity over the past 150 years [*Mann and Emanuel*, 2006], and longer records are needed to resolve how these climate forcings behave on timescales stretching into the mid-Holocene. Moreover, separation of these climatic drivers in our reconstruction is limited by an average sampling interval of 4–5 years and therefore a Nyquist frequency approaching 0.1. Therefore, increased efforts at generating high-resolution Holocene hurricane records are likely necessary to constrain what factors are influencing hurricane activity on such short timescales.

5. Conclusions

[34] Here, we developed a new proxy for reconstructing tropical cyclone frequency and used it to document substantial variability in North Atlantic hurricane activity in the Bahamas over the Holocene. Our results agree with previous studies which have emphasized the role of ENSO and the West African Monsoon in controlling late Holocene hurricane frequency and indicate that insolation may be important in the forcing mechanism of the North Atlantic storm intensity on millennial timescales. Indeed, the low frequency of storm events near the Bahamas during the mid-Holocene indicates that increased NH insolation and a related northward shift of the ITCZ may have worked to decrease major North Atlantic hurricane development. On shorter timescales (~11 years), we show that increases in solar radiation may

work to limit hurricane potential intensity by decreasing the ocean-atmosphere thermal gradient. However, a wider array of higher resolution records is needed to isolate this potential solar influence from other climate forcings (Atlantic Multidecadal Oscillation, Atlantic Dipole, ENSO, West African Monsoon) that are known to oscillate at similar frequencies. Here, we provide a blueprint for developing just such records. Ultimately, these methods provide an opportunity to use a large existing archive of carbonate bank cores (e.g., *Eberli et al.*, 1997) to reconstruct North Atlantic hurricane activity into the Late Pleistocene and beyond.

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