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Assessing sedimentary records of paleohurricane activity using modeled hurricane climatology

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[1] Patterns of overwash deposition observed within back-barrier sediment archives can indicate past changes in tropical cyclone activity; however, it is necessary to evaluate the significance of observed trends in the context of the full range of variability under modern climate conditions. Here we present a method for assessing the statistical significance of patterns observed within a sedimentary hurricane-overwash reconstruction. To alleviate restrictions associated with the limited number of historical hurricanes affecting a specific site, we apply a recently published technique for generating a large number of synthetic storms using a coupled ocean-atmosphere hurricane model set to simulate modern climatology. Thousands of overwash records are generated for a site using a random draw of these synthetic hurricanes, a prescribed threshold for overwash, and a specified temporal resolution based on sedimentation rates observed at a particular site. As a test case we apply this Monte Carlo technique to a hurricane-induced overwash reconstruction developed from Laguna Playa Grande (LPG), a coastal lagoon located on the island of Vieques, Puerto Rico in the northeastern Caribbean. Apparent overwash rates in the LPG overwash record are observed to be four times lower between 2500 and 1000 years B.P. when compared to apparent overwash rates during the last 300 years. However, probability distributions based on Monte Carlo simulations indicate that as much as 65% of this drop can be explained by a reduction in the temporal resolution for older sediments due to a decrease in sedimentation rates. Periods of no apparent overwash activity at LPG between 2500 and 3600 years B.P. and 500–1000 years B.P. are exceptionally long and are unlikely to occur (above 99% confidence) under the current climate conditions. In addition, breaks in activity are difficult to produce even when the hurricane model is forced to a constant El Niño state. Results from this study continue to support the interpretation that the western North Atlantic has exhibited significant changes in hurricane climatology over the last 5500 years.

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Theme: Interactions Between Climate and Tropical Cyclones on All Timescales
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1. Introduction

[2] Tropical cyclones are among the most hazardous of natural disasters, both in terms of human lives and economic loss. Although more rare, intense tropical cyclones (category 3 and greater, maximum sustained winds ≥96 knots or 49 m/s), are responsible for the vast majority of hurricane damage. For example, only 70 intense landfalling hurricane have occurred along the U.S. mainland since 1900 A.D., yet these extreme events are responsible for more than 85% of all normalized U.S. mainland hurricane damage between 1900 A.D. and 2005 A.D. [*Pielke et al.*, 2008]. The limited number of intense tropical cyclones within relatively short historical data sets limits our ability to confidently assess how climate variability may control intense hurricane activity, thus longer records are needed.

[3] Recent work shows that certain natural systems contain prehistoric archives of tropical cyclone activity [*Frappier et al.*, 2007a; *Nott*, 2004]. Proxies for tropical cyclones include, but are not limited to, negative δ^{18}O anomalies in speleothems and tree rings [*Frappier et al.*, 2007b; *Malmquist*, 1997; *Miller et al.*, 2006; *Nott et al.*, 2007], and storm-induced beach ridge, dune and coral rubble deposits along the coast [*Nott and Hayne*, 2001]. In addition, overwash deposits preserved within back-barrier lagoons, lakes and salt marshes have also provide a record of past tropical cyclone activity [*Donnelly et al.*, 2001a, 2001b, 2004a; *Donnelly*, 2005; *Donnelly and Woodruff*, 2007; *Liu and Fearn*, 1993, 2000]. Previously these overwash records have been used to estimate the reoccurrence frequencies for intense hurricane events to a location [*Donnelly et al.*, 2001b; *Liu and Fearn*, 1993] and for identifying shifts in hurricane climatology over the later Holocene [*Donnelly and Woodruff*, 2007; *Liu and Fearn*, 2000].

[4] *Donnelly et al.* [2001b] estimate probabilities for extreme storm inundation along the New Jersey coast based on salt marsh overwash layers associated with the Ash Wednesday Storm in 1962, the 1821 hurricane, and a paleoevent occurring between A.D. 1278 and 1438. In a similar study, *Liu and Fearn* [1993] use sand layers deposited in coastal Lake Shelby, Alabama over the last 3500 years to estimate the reoccurrence interval for hurricane-induce flooding to the lake. Given that no historical sand layers were observed in the center of the lake, it was inferred that prehistoric overwash deposits must represent events with intensities significantly greater than those observed for historical hurricanes strikes to the site (greater than category 3). Recently, *Elsner et al.* [2008] combined the average reoccurrence interval observed for paleostorm deposits at Lake Shelby with results from a statistical return-period model based on the "best track" hurricane data set in order to estimate the wind speed threshold required for overwash at the site. The analyses of *Liu and Fearn* [1993] and *Elsner et al.* [2008] both assume that hurricane climatology has remained constant over the last 3500 years.

[5] When developing centennial-scale to millennial-scale records of past hurricane occurrences at a site, it is necessary to assess whether observed variability is related to a changing climate or simply attributable to the random clustering of events under a steady climate. For example, if climate were to remain constant in time, what types of variability should be expected solely due to the random nature of hurricane strikes to a single site? In addition, with respect to overwash records, a storm deposit can only be clearly attributed to a single event if enough fine-grain lagoon or marsh sediment is deposited between overwash events. Sedimentary records are therefore prone to undercounting the exact number of overwash events at a site, especially during periods when sedimentation

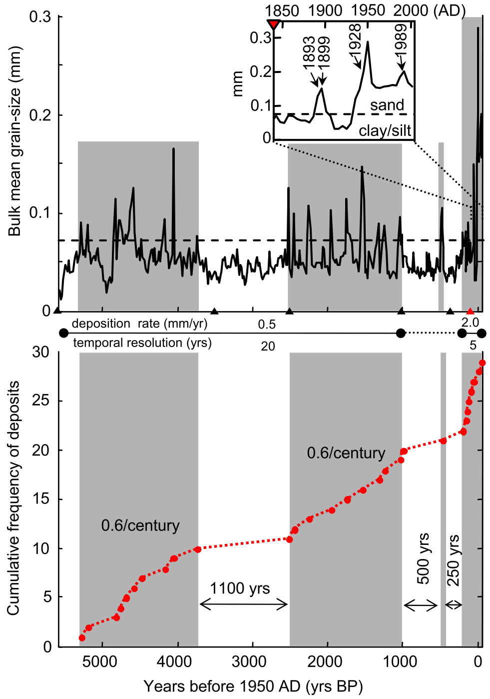

Figure 1. (top) Bulk mean grain size for core LPG4 plotted against sediment age. Depth to age conversion based on radiocarbon dates (black triangles) and 1840 A.D. land clearance horizon (red triangle) obtained by *Donnelly and Woodruff* [2007]. Dashed line represents grain size criteria used to identify coarse-grained deposits (>70 μm) and is at roughly the silt-to-sand transition. Inset shows historical sediments with noted hurricane deposits. (bottom) Cumulative frequency plot for overwash layers identified in Figure 1(top). Sedimentation rates and resulting temporal sampling resolutions are presented between top and bottom figures.

rates are low. Methods for assessing this potential for undercounting are required when sedimentary records with low or time-varying deposition rates are employed to assess the reoccurrence frequency of extreme events for a region.

[6] Here we develop a Monte Carlo technique for assessing the statistical significance for trends observed within sedimentary records of paleohurricane activity with time-varying sedimentation rates. A large number of separate time series (10^3) for maximum annual onshore wind speed are developed for a specific site using a random draw from an archive of simulated tropical cyclones, with statistical properties that conform to present-day climatology. Sedimentary records are generated for these time series using a prescribed threshold for overwash and a temporal resolution set by observed sedimentation rates at the site. As a test case, the technique is applied to a 5500 year paleohurricane reconstruction from Laguna Playa Grande (LPG), a coastal lagoon located on the small island of Vieques, Puerto Rico [*Donnelly and Woodruff*, 2007; *Woodruff et al.*, 2008], in order to assess the statistical significance for overwash trends observed at the site.

2. Description of Laguna Playa Grande Overwash Record

[7] *Donnelly and Woodruff* [2007] and *Woodruff et al.* [2008] provide a detailed description for the methods and analyses used to develop the 5500 year overwash reconstruction from LPG. Here we provide a summary. Sediment cores collected from the lagoon contain fine-grained organic mud episodically punctuated with coarse-grained event deposits. These coarser units are composed of material similar to that observed along the barrier beach (a mixture of siliciclastic rounded sand and shell material), and exhibit lateral sorting trends which are indicative of transport and deposition during extreme coastal inundation [*Woodruff et al.*, 2008]. Sediments collected throughout the lagoon exhibit similar temporal patterns in coarse grain deposition with recent event layers correlating well to the timing of intense hurricane strikes [*Donnelly and Woodruff*, 2007].

[8] For this study we choose to examine trends observed within the sedimentary record from core LPG4 (Figure 1), one of the primary cores used to develop the hurricane reconstruction for the site [*Donnelly and Woodruff*, 2007]. LPG4 was collected from the middle of the lagoon and likely provides the most complete record for overwash (sediments adjacent to the barrier were determined to be more susceptible to erosion and truncation during overwash, while sediments from more distal parts of the lagoon did not always receive enough coarse grained material to form identifiable event deposits). In total 29 deposits are evident in the LPG4 record (Figure 1). A comprehensive grain-size analysis of deposits for a core collected roughly 100 m to the north of LPG4, but with fewer chronological constraints, also reveals the same number of deposits as observed at LPG4 [*Woodruff et al.*, 2008]. Intervals of increased overwash activity observed at LPG4 are consistent with trends observed for additional cores collected from the site [*Donnelly and Woodruff*, 2007], with periods of more frequent overwash deposition occurring between approximately 5000–3600 years B.P., 2500–1000 years B.P., and 250 years B.P. to present (Figure 1).

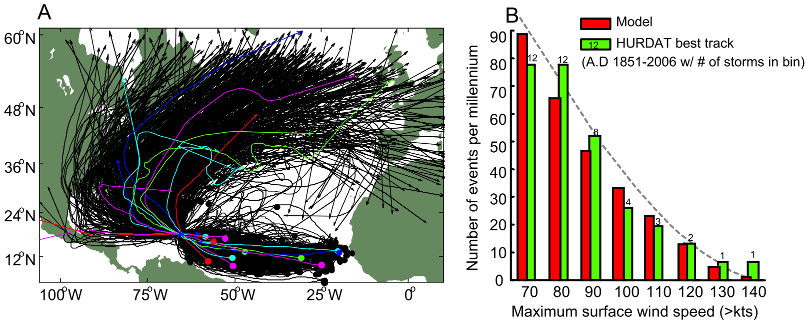

Figure 2. Path and intensity comparisons between modeled and historical hurricanes. (a) Historical (colored) and modeled hurricane tracks (black) passing within 75 km of Vieques. (b) Cumulative frequency distribution for maximum sustained wind speed for historical (green bars) and synthetic storms (red bars) shown in Figure 2a while passing within 75 km of Vieques. Grey dashed line represents the cumulative frequency distribution obtained using the peaks-over-threshold (POT) statistical model presented by *Elsner et al.* [2008].

[9] The reoccurrence frequency of identifiable event deposits at LPG4 is almost 4 times as large within historical sediments deposited since 1851 A.D. (~2.0 deposits/century) as those observed for the two earlier active intervals between 5000 and 3600 years B.P. and 2500–1000 years B.P. (~0.6 deposits/century). Although the high frequency of overwash occurrences within historical sediments may appear to be a period of unprecedented hurricane activity, it is also possible that it is an artifact produced solely by more storms being undercounted earlier in the record when sedimentation rates were significantly lower (Figure 1). For example, sedimentation rates since 1851 A.D. (~2.0 mm a^{-1}) are 4 times greater than rates observed within sediments older than 1000 years B.P. (~0.5 mm a^{-1}). These deposition rates correspond to temporal resolutions of 5 and 20 years per centimeter, respectively (sediment were sampled in 1 cm increments). The increased rate in accumulation for sediments deposited at LPG4 during the 19th century and 20th centuries is also common in other back-barrier marshes and lagoons along the western North Atlantic [*Donnelly and Bertness*, 2001; *Donnelly et al.*, 2004b; *Gehrels et al.*, 2005; *González and Törnqvist*, 2006] and has been interpreted to reflect increased rates of relative sea level rise during the last 100–200 years.

3. Methods

3.1. Generation of Synthetic Storm Archive for Laguna Playa Grande

[10] Over the last 150 years only three or four hurricanes have been intense enough to produce an identifiable overwash deposits in the central portion of LPG (Figure 1). To overcome restrictions associated with this limited number of historical overwash events, we use the stochastic and deterministic model developed by *Emanuel et al.* [2006] to generate a large number of synthetic tropical cyclones passing within 75 km of LPG (Synthetic Tropical Cyclone Climatology). The model was used to generate a statistical database of over 10,000 "years" of storm impacts (from tropical depressions to category 5 storms; assuming modern climatic conditions).

[11] Synthetic storms are initiated using a random draw of observed genesis locations from the tropical cyclone best track data set since 1970 A.D. and based on the space-time probability distribution developed for these storms. Once generated, storm tracks are determined using a beta and advection model (BAM); the second track generation technique described by *Emanuel et al.* [2006]. The BAM technique propagates storms through randomly generated wind fields which conform to the monthly means, variances, and covariances derived from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis data set (developed by assimilating global atmospheric data for the years of 1957 A.D. to 1996 A.D. [*Kalnay et al.*, 1996]). The time varying intensity for each storm is modeled numerically using the Coupled Hurricane Intensity and Prediction System (CHIPS), as described by *Emanuel et al.* [2004]. Wind fields for each storm in the CHIPS model are framed in angular momentum coordinates, permitting a very high resolution of each storm's inner core.

[12] Three thousand synthetic storms passing within 75 km of LPG were generated, with a total model run time of 10,563 years, and yielding an average reoccurrence rate of 0.284 storms a^{-1} for the site. The tracks of these simulated storms

typically fit within the bounds for the 12 observed hurricanes passing within 75 km of LPG since 1851 A.D. (Figure 2a). Both modeled and historic hurricanes primarily develop to the east of the site within in the Main Development Region of the Atlantic (10°–20°N [*Goldenberg et al.*, 2001]) and typically track either up the eastern seaboard of the United States or back out into the North Atlantic once passing the site. In addition to storm tracks, the distribution of intensities for the 3000 simulated storm events is also reasonable when compared to the distribution of intensities for historical hurricanes affecting the site (Figure 2), especially considering the scarcity of major hurricanes within the documented data set. The distribution of modeled storm intensities are also similar to the distributions obtained using the alternative peaks-over-threshold (POT) statistical method put forth by *Elsner et al.* [2008] (Figure 2b). This comparison provides additional validation for the *Emanuel et al.* [2006] model because the two approaches are fundamentally different, with obtained statistical parameters for the POT method derived solely using the best track data set, while the *Emanuel et al.* [2006] model uses the best track data set only to determine genesis locations, with storm tracks and intensities derived independently using the 40 year NCAR/NCEP reanalysis data set.

3.2. Criteria for Overwash at Laguna Playa Grande

[13] Hurricane-induced flooding at LPG is primarily due to the combination of storm surge and wave runup [*Woodruff et al.*, 2008], where storm surge is the rise in water elevations due to wind and pressure [*Simpson and Riehl*, 1981] and wave runup is the time varying rise in water elevations at the shoreline due to breaking waves [*Stockdon et al.*, 2006]. At landfall, storm surge is typically highest in the front right quadrant of a hurricane (when located in the Northern Hemisphere), where rotational winds and the storm's translational speed constructively act to elevate water levels [*Simpson and Riehl*, 1981]. Storm surges can also be amplified by shallow sloping bathymetry and concave coastlines [*Jelesnianski et al.*, 1992]. In the case of LPG, however, the relatively straight coastline and steep offshore bathymetry reduces the influence of storm surge [*Mercado*, 1994; *Woodruff et al.*, 2008]. In addition, the timing of a storm strike in relation to the lunar tidal cycle is less important at LPG because the tidal range is small (~0.2 m).

[14] In areas where storm surges are moderate, such as at LPG, elevated water levels along the coast due to breaking waves can be more important for determining the magnitude of barrier inundation. Waves are typically the largest in the front right quadrant of a hurricane [*Wright et al.*, 2001]. Therefore, similar to storm surge, wave runup is also likely most pronounced at LPG when the front right quadrant of a storm strikes the site from the south. Storm winds and the resultant flooding potential generally diminish away from the storm's radius of maximum wind. Consequently, wind speeds and flooding at a site can be equal for category 3 and category 5 hurricanes of equal size if the weaker of the two storms passes significantly closer to the site. For this analysis we therefore assume that the magnitude of overwash at LPG is directly related to the maximum onshore wind speed occurring at the site during each modeled storm event, rather than the overall intensity of the event.

[15] On the basis of the best track data set, historical overwash deposits at LPG4 are all attributed to hurricanes whose maximum sustained wind speeds were at or in excess of 100 knots (51 m/s) while passing nearby the site (1989 A.D., 1928 A.D., 1899 A.D., and 1893 A.D.). The threshold wind speed required for overwash deposition at LPG4 therefore appears to be less than 100 knots. Further, no evidence for overwash deposition was observed for two slightly less intense hurricanes passing just to the south of the site with maximum sustained wind speeds of 90 knots or 46 m/s (1876 A.D. and 1998 A.D.). Since 1983 A.D. the National Hurricane Center has used satellite data to provide additional information with respect to a storm's windfield distribution [*Demuth et al.*, 2006]. This "extended best track" data set indicates that the 1998 A.D. Georges Hurricane had a radius of maximum wind of 45 km and likely passed within approximately 10 km of the site. Hurricane Georges therefore likely struck the site near its maximum sustained wind speeds of 90 knots, but did not leave a deposit at LPG4. Accurate windfield data for the 1876 A.D. hurricane is not available; however, the best track data set indicates that the storm also passed within ~10 km of the site with maximum sustained winds of 90 knots. Therefore, onshore winds at the site during the 1876 A.D. hurricane likely approached 90 knots, but similar to Hurricane Georges, did not leave a layer at LPG4. On the basis of the data available it appears that an approximate constraint of at least 90 knots but no more than 100 knots roughly bound the threshold wind speed required for depo-

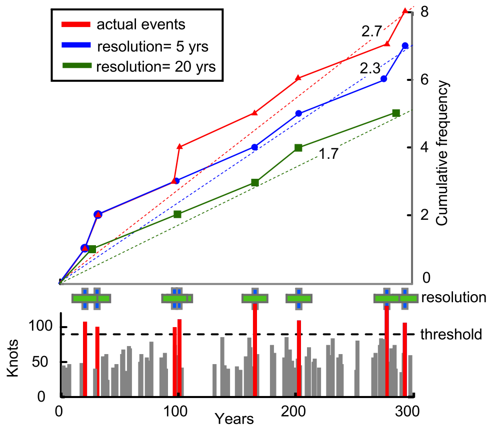

Figure 3. Example of synthetic overwash record. (bottom) A 300 year synthetic overwash record created for Vieques. Gray bars indicate maximum onshore winds recorded at the site using a random draw of synthetic storms. Red bars indicate storms which exceed the threshold (horizontal black dashed line) required for overwash to occur at the site. The blue and green bars above the wind reconstruction indicate discernable periods of overwash for temporal resolutions of 5 years and 20 years, respectively. (top) Actual (red) and discernable cumulative frequencies for a temporal resolution of 5 years (blue) and 20 years (green) for the synthetic overwash record in bottom plot. Numbers indicate the rate of resolvable overwash events per century based on the indicated temporal resolutions.

sition at LPG4 in its modern geomorphic configuration, although these bounds are presented acknowledging that maximum wind speeds in the best track are estimates with a relatively high level of uncertainty.

3.3. Monte Carlo Simulations for Hurricane Deposition

[16] To obtain probability distributions for overwash rates at LPG for a specified period of time under modern hurricane climatology we first use a random draw from the synthetic storm archive to generate 10^3 separate records of storm occurrences at the site, all with the same set duration (see Figure 3 for example). Storms are selected for a given year only if a randomly generated number from 0 to 1 exceeds the probability determined for a storm occurrence. The arrival of a storm to the site is treated as a Poisson process [*Bove et al.*, 1998; *Elsner and Bossak*, 2001], such that the probability, P, for k number of storms to occur during any given year is obtained by:

$$P = \frac{e^{-\lambda}\lambda^k}{k!}$$

Here λ is the average annual storm occurrence frequency determined by the *Emanuel et al.* [2006] hurricane model (i.e., 0.284 storms a^{-1}).

[17] Overwash deposition is identified within each time series when a storm's maximum onshore wind speed at the site exceeds the site's flooding threshold. Each of these identified overwash events are then assigned a time interval based on a specified temporal resolution. For example, a storm layer occurring at year 250 with a temporal resolution of 20 years would be given a time period beginning at year 240 and ending at year 260. If the intervals between two or more individual storms overlap then only one deposit is created since these separate storm layers would not likely be distinguishable within the sedimentary record (Figure 3).

4. Results

4.1. Model-Observation Comparison for Historical Sediments

[18] To assess how well simulated overwash records reproduce hurricane deposition at the site, we first compare simulated and observed overwash rates for sediments deposited at LPG4 over the historical record from 1851 A.D. to 2006 A.D (Figure 4a). One thousand synthetic overwash records, all 156 years in length, are constructed at the temporal resolution obtained for modern sediments (5 a cm^{-1}). Runs are then assessed using threshold onshore wind speeds from 70 to 120 knots at 10 knot increments (or 36 m s^{-1} to 62 m s^{-1} at 5.2 m s^{-1} increments).

[19] Since 1851 A.D. four hurricanes with onshore winds in excess of 90 knots have struck Vieques, resulting in three recognizable deposits at LPG4 (Figure 1). Our best estimates for the actual and resolvable rates of overwash activity over the last 156 years in core LPG4 are therefore 2.6 events per century and 1.9 deposits per century, respectively. Simulated reoccurrence rates are consistent with these observations using threshold onshore winds of 90 and 100 knots (Figure 4a). However, a 90 knots exceedance threshold appears to produce overwash results more consistent with historical rates obtained from LPG4. For instance, 2.6 events per century and 1.9 deposits per century are well within one standard deviation (1σ) for the model's simulated distributions using an exceedance threshold of 90 knots but above 1σ for 100 knots (Figure 4a).

[20] Overwash simulations for historical sediments suggest that on average, 11% of overwash events

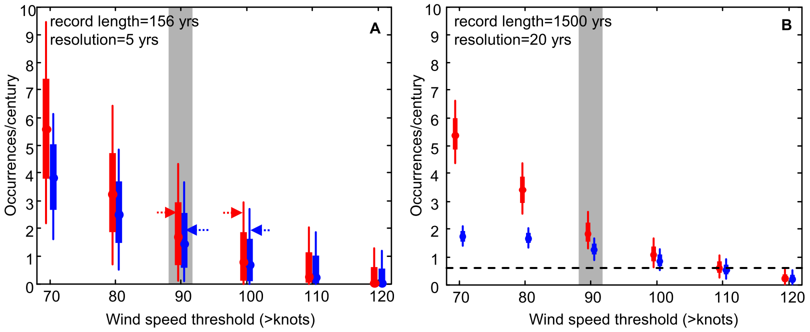

Figure 4. Model distributions predicted for events/century (red) and resolvable deposits/century (blue) using modern hurricane climatology and with varying wind speed exceedance thresholds required for overwash. Median (circle), 16th-to-84th percentiles (thick line), and 2.5-to-97.5 percentiles (thin line) are presented. Shading indicates estimated current 90 knot wind speed threshold required for overwash deposition at LPG4. (a) Results for 156 year simulations at a temporal resolution of 5 years. Actual overwash occurrence rate based on historical observation (red arrows) and number of deposits observed within historical sediments at LPG4 (blue arrows) are noted. (b) Same as Figure 4a but for 1500 year simulations with a temporal resolution of 20 years. Dashed line in Figure 4b represents actual overwash occurrence rate observed between 2500 and 1000 years B.P. at LPG4 (Figure 1).

occurring at the site would be missed in the depositional record due to undercounting (assuming a 90 knot exceedance threshold). A comparison between historic deposits in LPG4 and hurricanes from the best track data set suggest that 1 out of 4 overwash events were likely missed over the last 156 years or a 25% reduction due to undercounting. Although this percentage is above the average obtained by model simulations, it is within the range of acceptable values based on the probability distributions obtained using such a short record (13% of the historical overwash simulations resulted in an undercounting of 25% or more for an exceedance threshold of 90 knots). Model simulations therefore are consistent with observations for historical sediments at LPG4.

4.2. Assessment for Earlier Active Intervals at LPG

[21] The correspondence between modeled and observed overwash rates at LPG4 for historical sediments supports applying the model to evaluate trends observed within the paleorecord. Ten overwash layers are identified at LPG4 between 1000 and 2500 years B.P. resulting in approximately 0.6 resolvable deposits per century, a rate approximately 4 times smaller than what is observed within sediments deposited over the last 300 years (Figure 1). As discussed previously, this drop in activity may be due in part to the decreased sedimentation rates observed within these older sediments. To assess the effects of undercounting during the active interval between 1000 and 2500 years B.P., we generate additional synthetic overwash records under the present hurricane climatology, but for durations of 1500 years and with a decreased temporal resolution of 20 years.

[22] Under the same hurricane climatology, the 1500 year simulations produce the same average number of events per century as the 156 year runs (1.9 events per century, Figures 4a and 4b). However, extending the record length to 1500 years significantly reduces the variance about this mean. For instance, the 5th and 95th percentiles for simulations of 1500 years using a 90 knot exceedance threshold are 1.4 and 2.5 events/century, compared to a range of 0 to 3.7 events/century for the 156 year long runs. This over threefold decrease in variance for the 1500 year simulations demonstrates that millennial-scale changes in overwash activity can be assessed at a much greater confidence level at LPG than changes occurring on shorter decadal or centennial timescales.

[23] As expected, the rates of resolvable deposits per century decrease when temporal resolutions are reduced from 5 to 20 years (Figures 4a and 4b). On average, 32% of overwash events were missed using a temporal resolution of 20 years and an exceedance threshold of 90 knots, compared to only 11% for similar runs with a temporal resolution of 5 years. The 5th and 95th percentile bounds for resolvable rates of overwash for the 1500 year simulations are 0.9 and 1.6 deposits per century for an onshore wind speed threshold of 90 knots. Interestingly, although the number of resolvable deposits per century decreases significantly using a 20 year resolution, this drop is still not enough to completely explain the lower activity observed

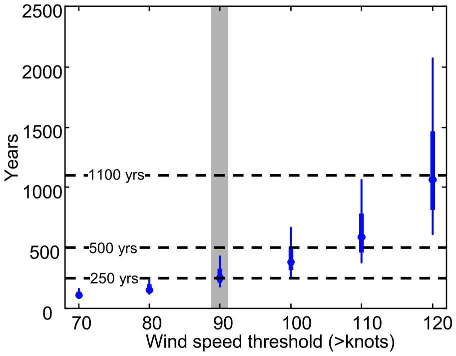

Figure 5. Model distribution for maximum time period without an overwash occurrence in simulations of 5500 years for varying exceedance onshore wind speeds required for overwash. Median (circle), 16th-to-84th percentiles (thick line), and 2.5-to-97.5 percentiles (thin line) are presented. Shading indicates estimated 90 knot threshold currently required for overwash deposition at LPG4. Horizontal dashed lines indicate intervals of inactivity observed at LPG4 (Figure 1).

between 2500 and 1000 years B.P. (0.6 deposits per century) relative to the last 300 years.

[24] Our simulations indicate that a rate of 0.6 deposits per century is possible under the current hurricane climatology if the barrier's exceedance threshold was raised from 90 to 110 knots or to 57 m s^{-1} (Figure 4b). Such an increase could occur if the elevation of the barrier relative to sea level was higher between 1000 to 2500 years B.P. compared to its present elevation. However, an increase in the barrier's elevation between 1000 and 2500 years B.P. with no change to hurricane climatology should systematically decrease the flooding depth over the barrier during this interval. *Woodruff et al.* [2008] inversely modeled flooding magnitudes over the barrier at LPG based on the distribution of grain sizes for all 29 overwash deposits observed at the site. Results from the study show no systematic decrease in flooding magnitude for deposits occurring between 1000 and 2500 years B.P. when compared to historical overwash layers. Therefore, the drop in overwash rates between 1000 and 2500 years B.P. does not appear to be a result of changes to the barrier morphology.

[25] On the basis of our analyses, we estimate that at least 35% of the decrease in apparent overwash activity observed in Figure 1 between 1000 and 2500 years B.P. (compared to rates over the last 300 years) is due to a change in regional hurricane activity, with the rest likely an artifact produced solely by decreased sedimentation rates during this interval.

4.3. Assessment for Periods of Inactivity at Laguna Playa Grande

[26] In addition to the periods of apparent increased overwash activity, the LPG4 reconstruction also exhibits three extended intervals with no evidence for overwash deposition (3600–2500 years B.P., 1000–500 years B.P., and 500–250 years B.P., Figure 1). To assess the likelihood of a millennial scale record containing gaps of this duration under the current hurricane climatology we generate 10^3 synthetic overwash records from the site, all with a duration equal to the length of the entire LPG4 record (5500 years). Probabilities are then calculated for the maximum length of inactivity produced by these simulations for varying wind speed exceedance thresholds (Figure 5). The median value for the maximum gap in activity during these 5500 year simulations was 265 years for an exceedance wind speed threshold of 90 knots, with only 5% of these simulations exhibiting a period of inactivity greater that 400 years. The 500 year and 1100 year intervals of no apparent overwash deposition between 3600 and 2500 years B.P. and 1000–500 years B.P. are therefore significant (above 99% confidence), and likely represent either times when overall hurricane occurrences were lower than today, or periods when the required wind speed threshold for overwash at the site was greater. The 250 year gap in overwash deposition at LPG4 between 500 and 250 years B.P. is below the median value of 265 years for these 5500 year simulations (Figure 5), indicating that this inactive interval is by itself less noteworthy. However, *Donnelly and Woodruff* [2007] show that a period of reduced activity observed between 1000

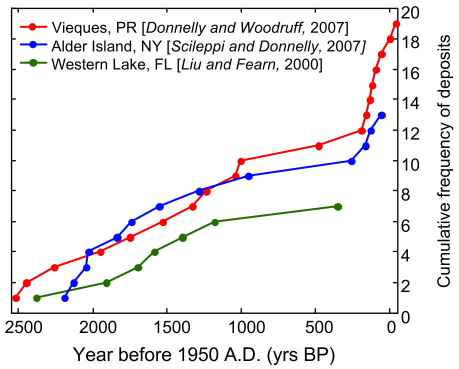

Figure 6. Cumulative frequency plots since 2500 years B.P. for millennial-scale hurricane overwash reconstructions collected from Laguna Playa Grande (red), New York (blue), and the Gulf Coast of Florida (green). Overwash records from the western North Atlantic exhibit similar trends, including a break in activity between 1000 and 500 years B.P.

and 250 years B.P. is also observed in hurricane overwash reconstructions developed from both New York [*Scileppi and Donnelly*, 2007] and the Gulf Coast [*Liu and Fearn*, 2000] (Figure 6).

[27] A drop in relative sea level at approximately 1000 years B.P. could result in a synchronous rise in elevation for these separate barrier systems, and a resultant increase in flooding magnitudes required for hurricane overwash at all three locations. However, sea level reconstructions from all three regions indicate a period of relatively slow sea level rise over the last 6000 years [*Donnelly and Webb*, 2004; *Lighty et al.*, 1982; *Tornqvist et al.*, 2004], with no evidence for any sudden drop at approximately 1000 years B.P. Therefore, the evidence to date suggests that the period of inactivity at LPG4 between 1000 and 250 years B.P. represents a decline in western North Atlantic hurricane activity relative to current hurricane climatology, rather than synchronous local alterations to barrier morphology at the LPG, New York, and Gulf Coast sites.

4.4. El Niño Simulations

[28] A comparison of the LPG overwash reconstruction and a proxy record of El Niño events from Laguna Pallcacocha, Ecuador [*Moy et al.*, 2002] suggests that the gap in overwash activity between 1000 and 500 years B.P. (and likely to 250 year B.P.) coincides with a period of more frequent, moderate-to-strong El Niño events [*Donnelly and Woodruff*, 2007]. This is consistent with observations from the instrumental record, which indicate that North Atlantic hurricane activity is generally suppressed during El Niño years [*Bove et al.*, 1998; *Elsner et al.*, 2001; *Gray*, 1984; *Pielke and Landsea*, 1999]. For instance, overall hurricane activity in the Atlantic diminishes on average to 80% of the long-term mean (since A.D. 1950) during the 19 El Niño years identified using the criteria of *Pielke and Landsea* [1999], where weak-to-strong El Niño years are identified when the 3-month mean SST anomaly for the Niño 3.4 region (5°N–5°S, 120°–170°W) for August–October is at or exceeds 0.4°C.

[29] On the basis of the available evidence, *Donnelly and Woodruff* [2007] concluded that variability in the El Niño/Southern Oscillation (ENSO) over the last several millennia has likely played an important role in controlling the frequency of intense hurricanes in the western North Atlantic. However, making quantitative estimates of the influence of El Niño on overwash activity at LPG was difficult because of the relatively short instrumental record. As an alternative in this study, we again employ the *Emanuel et al.* [2006] hurricane model to generate a large number of synthetic hurricanes for LPG using reanalysis data for just the 19 El Niño years since A.D. 1950. To simulate the inactive period between 1000 and 500 years B.P., 1000 five hundred-year-long overwash records are generated using a random draw from this El Niño storm archive, which likely represent the extreme condition of a constant El Niño like state at LPG. These simulations therefore provide a valuable climatic end-member that can be used to assess the degree to which El Niño alone could be responsible for the patterns observed in the LPG record.

[30] Hurricane tracks are generated for El Niño years using the techniques described by *Emanuel et al.* [2008]. For these simulations the hurricane model is driven using reanalysis data for the 19 El Niño years following A.D. 1950. The number of genesis points occurring over just 19 years is likely too few to obtain representative genesis probabilities for El Niño conditions. As an alternative, we apply the random storm seeding technique described by *Emanuel et al.* [2008]. Weak warm core vortices with peak circular wind speed of only 25 knots (12 m/s) and a relatively low midlevel humidity anomaly are distributed randomly everywhere northward of 2°N and at all times. Vortices are propagated forward using the beta-and-advection (BAM) model but are steered with randomly generated wind fields conforming to reanalysis statistics for just El Niño years. The CHIPS model described by *Emanuel et al.* [2004] is used to determine whether these weak vortices either decay away or intensify into actual storms. To account for increased wind shear observed during El Niño years, the CHIPS model employs the same El Niño wind fields generated initially for the BAM track model. Vortices are positively identified as a storm only if winds develop to at least 40 knots (21 m s^{-1}) and are selected for the LPG El Niño storm archive when these disturbances pass within 75 km of the site. Finally, for this analysis the average radius of maximum winds for ENSO runs are adjusted to the average radius of maximum winds for the original runs to account for differences associated with the initialization methods for these two separate simulations.

[31] Apparent overwash activity is reduced at Laguna Playa Grande for the 500 year El Niño simulations to rates of between 0.3 and 1.4 deposits per century (5th and 95th percentiles), compared to

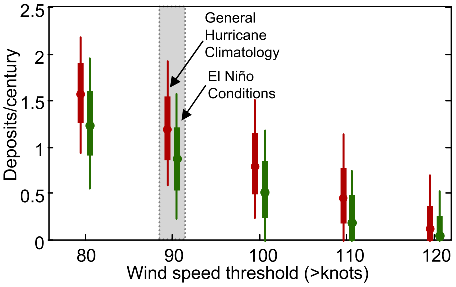

Figure 7. Model distributions for discernable deposits/century for both overall hurricane climatology (red) and El Niño conditions (green) at Laguna Playa Grande for a period of 500 years and a temporal resolution of 20 years. The format is the same as in Figure 4 with median (circle), 16th-to-84th percentiles (thick line), and 2.5-to-97.5 percentiles (thin line). Shading denotes estimated current 90 knot wind speed threshold required for overwash deposition at LPG4. Overwash activity is reduced for the El Niño runs but not enough to explain the total lack of overwash activity observed at LGP4 between 1000 and 500 years B.P.

the higher range of 0.7 to 1.8 deposits per century for similar runs using general hurricane climatology (Figure 7). These results suggest that hurricane suppression by a change in the ENSO, even under a constant El Niño state, is not sufficient to completely explain the break in overwash activity observed at LPG between 1000 and 500 year B.P. (assuming a wind speed exceedance threshold of 90 knots).

[32] Increasing the site's exceedance threshold for overwash to 120 knots could explain the break in activity between 1000 and 500 years B.P. (Figure 7); however, as discussed earlier, this is unlikely given evidence of decreased overwash activity observed during this same interval in both the New York and Gulf Coast reconstructions (Figure 6). Results from this analysis therefore suggest that other climate forcings in addition to increased El Niño activity are likely required to explain the dramatic decline in overwash activity observed between 1000 and 500 years B.P. at the LPG, New York, and Gulf Coast sites.

5. Discussion

[33] Simulations for El Niño conditions suggest that large-scale climatic changes in addition to ENSO variability are required to produce the trends observed for the current paleohurricane reconstructions from the western North Atlantic. A reconstruction of diatomic assemblages from Lake Ossa, West Cameroon [*Nguetsop et al.*, 2004] indicates a decrease in African monsoon strength occurring at approximately 1000 years B.P. This decrease may have further suppressed hurricane activity in the Atlantic [*Donnelly and Woodruff*, 2007]. In addition, a recent high resolution SST reconstruction from the northern Gulf of Mexico exhibits a rapid 3°C drop in temperature at approximately 1000 years B.P. and a later increase in SST beginning at 250 years B.P. (Figure 8a [*Richey et al.* [2007]). A drop in SST is also evident at approximately 1000 years B.P. in a lower resolution sedimentary record collected off the southwest coast of Puerto Rico (Figure 8b [*Nyberg et al.*, 2002]) but with no indication of an increase in SST at 250 years B.P. In addition, the *Nyberg et al.* [2002] record suggests that SSTs off of southern Puerto Rico have generally been cooler than present over the last 2000 years; whereas, the recent results from the Gulf of Mexico suggest that prior to ~1000 years B.P, SSTs in this region were warmer than modern SSTs. The discrepancies between these two records stress the need for additional high-quality SST reconstructions from other regions of the western North Atlantic in order to evaluate how past changes in SST, both regional and basin-wide, have affected hurricane activity. Further, additional storm reconstructions from the western North Atlantic will provide additional assessments for the

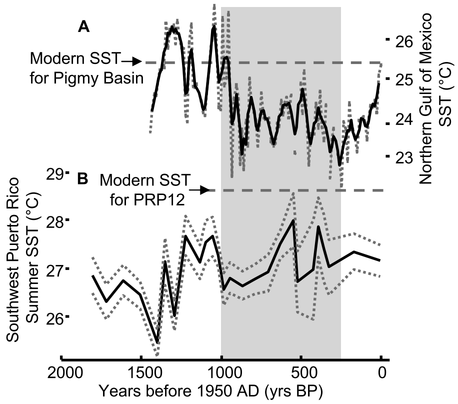

Figure 8. (a) Mg/Ca sea surface temperature (SST) reconstruction for Pigmy Basin in northern Gulf of Mexico [*Richey et al.*, 2007]. Markers represent individual measurements and solid line indicates three-point running mean. (b) Reconstruction of summer SSTs ~10 km offshore of southern Puerto Rico from core PRP12 (solid line) with 2σ uncertainties (dotted lines) [*Nyberg et al.*, 2002]. Dashed lines in Figures 8a and 8b indicate current SST estimates at each coring location. Discrepancies exist between the two SST reconstructions; however, both suggest a drop in temperature at ~1000 years B.P.

trends observed within the LPG, New York, and Gulf Coast overwash reconstructions.

6. Conclusions

[34] Here we describe a new technique for assessing trends observed within sedimentary records of paleohurricane activity and apply it to a 5500 year reconstruction from Vieques, Puerto Rico. The fourfold decrease in apparent overwash rates at Vieques between 2500 and 1000 years B.P. when compared to apparent overwash rates during the last 300 years is determined to be largely an artifact resulting from decreased sedimentation rates during this interval, although at least 35% of the apparent drop in activity during this interval is likely due to a reduction in the overall rate of hurricane landfalls to the site. Simulations indicate that breaks in activity observed between 2500 and 3600 years B.P. and 500–1000 years B.P. in the Vieques record are exceptionally long and unlikely to occur under the current hurricane climatology. Further, additional overwash reconstructions from the northeastern United States and Gulf Coast exhibit similar patterns of deposition over the last 2500 years, with a decline in overwash frequency occurring in all these records between 250 and 1000 years B.P. The gap in activity occurring during this interval is significant and difficult to produce even when the hurricane model is forced to a constant El Niño state. Results from this study provide further evidence that the Western Atlantic has experienced statistically significant changes in hurricane climatology since 5500 years B.P.

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