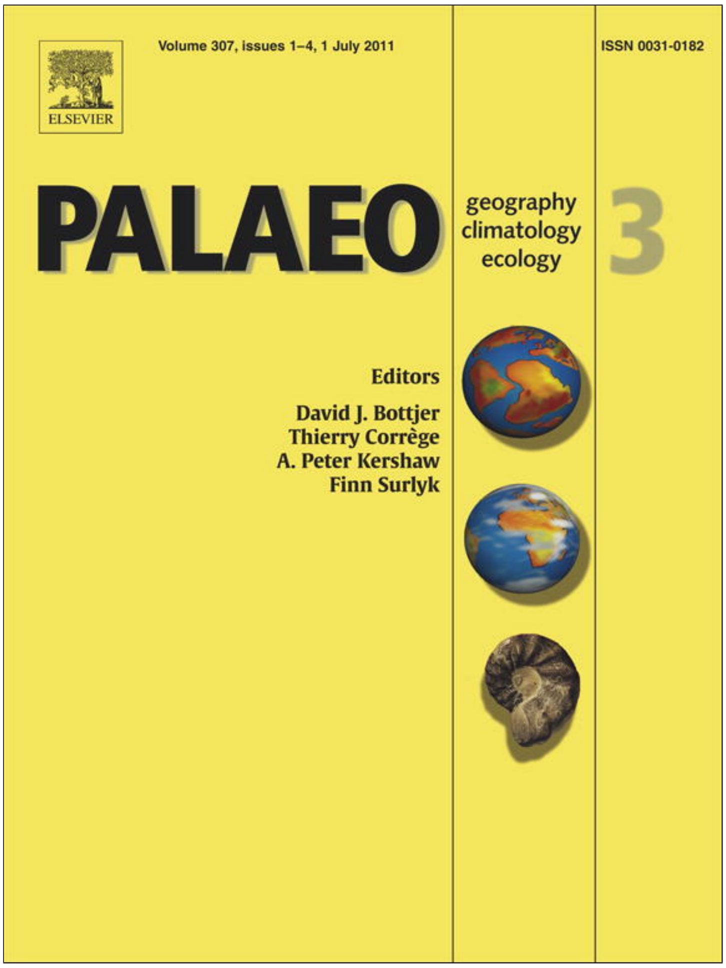
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Testing coral-based tropical cyclone reconstructions: An example from Puerto Rico

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ABSTRACT

Complimenting modern records of tropical cyclone activity with longer historical and paleoclimatological records would increase our understanding of natural tropical cyclone variability on decadal to centennial time scales. Tropical cyclones produce large amounts of precipitation with significantly lower $\delta^{18}O$ values than normal precipitation, and hence may be geochemically identifiable as negative $\delta^{18}O$ anomalies in marine carbonate $\delta^{18}O$ records. This study investigates the usefulness of coral skeletal $\delta^{18}O$ as a means of reconstructing past tropical cyclone events. Isotopic modeling of rainfall mixing with seawater shows that detecting an isotopic signal from a tropical cyclone in a coral requires a salinity of ~33 psu at the time of coral growth, but this threshold is dependent on the isotopic composition of both fresh and saline end-members. A comparison between coral $\delta^{18}O$ and historical records of tropical cyclone activity, river discharge, and precipitation from multiple sites in Puerto Rico shows that tropical cyclones are not distinguishable in the coral record from normal rainfall using this approach at these sites.

1. Introduction

Tropical cyclones can cause devastating damage, making an understanding of the controls on their natural variability and improvements in tropical cyclone prediction important. Accurate hourly to seasonal-scale predictions have become commonplace, enabling people to prepare for events and mitigate impacts. However, modern anthropogenic climate change is expected to cause changes in the patterns of tropical cyclone frequency, intensity and location (e.g., Bender et al., 2010; Bengtsson et al., 2006; Webster et al., 2005). Such changes will occur over decades and centuries, highlighting the need for tropical cyclone predictions based on an understanding of the controls on tropical cyclone variability over such time scales.

Records of tropical cyclones were not originally designed for climatological research and are fraught with issues regarding completeness and changing observation methods (Landsea, 2007). Historical and geologic archives (e.g., Donnelly et al., 2001; Partagas and Diaz, 1996) can supplement existing tropical cyclone data, which currently extend back to only the mid 20th century in the Pacific and to 1851 in the Atlantic. Information from historical archives can increase the accuracy of existing storm records by documenting previously un-recorded events or by providing new information about known events. Donnelly and Woodruff (2007) demonstrated the value of sedimentary overwash deposits, geologic features that have been studied in the geological literature for many years (e.g., Hayes, 1967), for addressing questions about tropical cyclone activity on millennial time scales. Dating constraints and sedimentation rates limit the utility of such features to address decadal- to centennial-scale variability. The development of higher resolution proxies to address the causes of variability over decades to centuries would help to refine current predictive models.

Frappier et al. (2007a) suggested that coral skeletal records were potential archives of tropical cyclone activity, which, along with speleothems, could help fill the temporal gap described above. Corals live in shallow tropical oceans and therefore have an ideal distribution for recording tropical cyclone activity. Paleoclimate reconstructions based on corals can have sub-annual resolution, extend for multiple centuries, and are useful for addressing decadal- to centennial-scale climate variability (e.g., Druffel, 1997). Published coral-based tropical cyclone activity reconstructions (Greer and Swart, 2006; Nyberg et al., 2007) link tropical cyclone activity to runoff recorded in the corals and assume stationarity in the relationship between local runoff and tropical cyclones or another derived parameter (e.g., wind shear). One flaw in this approach is that the coral does not record individual events uniquely. For example, a season with more than normal afternoon thundershowers could impart the same signal as a season with several tropical cyclones. Analyzing potential changes in the relationships between climate variables and tropical cyclones is a major goal for long-term tropical cyclone reconstructions; assuming stationarity in the relationships creates circular reasoning in this line of investigation.

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Tropical cyclone-related precipitation has lower $\delta^{18}O$ values than everyday convective precipitation (Lawrence, 1998; Lawrence and Gedzelman, 1996; Lawrence et al., 2002; Lawrence et al., 1998), so that individual tropical cyclones may be identified through their unique $\delta^{18}O$ signature. This method avoids the assumption of stationarity in the relationship between runoff and tropical cyclones. Such a record would permit the study of the relationships between climate variables and tropical cyclones without circular reasoning.

The current work stems from an observation published by Kilbourne et al. (2008) that coral $\delta^{18}O$ from a site in southwestern Puerto Rico did not contain a seawater $\delta^{18}O$ signal expected during the passing of hurricane Hortense. The lack of a $\delta^{18}O$ response to a tropical cyclone was surprising and has lead us to quantitatively explore the seawater $\delta^{18}O$ signals from tropical cyclones and to test if corals from other locations provide similar results.

The study presents a two end-member mixing model used to calculate the expected seawater isotopic signal a coral might experience during tropical-cyclone-related precipitation. The model provides information about the conditions required for tropical cyclone signal detection in the coral skeletal $\delta^{18}O$ record. These expectations are tested against the Kilbourne et al. (2008) data and against two new coral $\delta^{18}O$ data sets from two other sites in Puerto Rico, which the modeling effort indicates are ideal for capturing tropical cyclone-related $\delta^{18}O$ signals. The resulting tropical cyclone reconstructions are statistically compared to predictions based on the local tropical cyclone return period to test for significant reconstruction skill. Finally, we discuss the implications of our results for future attempts to reconstruct tropical cyclones using rainfall $\delta^{18}O$ anomalies. Studies such as this one can serve as a model for understanding the storm-related isotopic signals found in tree rings and cave deposits.

2. Methods

2.1. Modeling seawater $\delta^{18}O$ responses to rainfall

A two end-member mixing model served to estimate oxygen isotopic ratios in the surface ocean when tropical-cyclone-derived rain mixes with seawater. Gradually increasing amounts of fresh water, mixed into either a 5 m or 10 m water column within the model, drove changes in salinity and oxygen isotopic values. Mixing during tropical cyclones is often much deeper than 10 m (e.g., Black and Dickey, 2008), but the coral samples grew at about 5 m depth and most coral cores are recovered from <10 m, so the model assumed full water column mixing of the tropical storm precipitation in shallow water. The seawater end-member represents local summer conditions determined by measurements of salinity and oxygen isotopic composition made over several years in southwestern Puerto Rico (Watanabe et al., 2002) with an oxygen isotopic composition and salinity of 0.5‰ SMOW and 35 psu respectively.

The model used three different freshwater end-members. One end-member represented average rainfall in the area with an oxygen isotopic value of −6.5‰ SMOW, and was derived from the zero salinity intercept of the local salinity and seawater $\delta^{18}O$ regression line (data from Watanabe et al. (2002)). Two tropical cyclone rainfall end-members with oxygen isotopic compositions of −10 and −15‰ SMOW, were based on the composition of rainfall from past tropical cyclones that made landfall along the southern United States (Lawrence, 1998). Lawrence et al. (1998) measured stable isotope ratios in rainfall associated with Hurricane Luis, which passed by Puerto Rico in 1995. The hurricane was 190 km northeast of the island at its closest point, so they were able to obtain precipitation samples from only the outer edge of the storm, which were slightly more depleted with respect to ^{18}O (−8.8‰ SMOW) than the long-term average precipitation (−6.5‰ SMOW).

2.2. Testing the coral records

2.2.1. Study sites

The coral records used to test our tropical cyclone reconstruction came from study sites representing three different environmental settings around the island of Puerto Rico (Fig. 1, Table 1). Turrumote reef, off shore from the village of La Parguera, is the site in this study with the least amount of influence from terrestrial run off. The reef lies 3 km from shore, near the outer edge of the wide continental shelf (Fig. 1C). A coastal ridge forms a barrier to water flowing off the Cordillera Central, creating a minuscule watershed that drains only the immediate coastal zone. The coastal zone around La Parguera lies within the driest region of Puerto Rico, on the leeward southwest corner of the island (Carter and Elsner, 1996), keeping runoff from the small watershed to a minimum.

The second study site was also located in the southwest region of Puerto Rico and was at the mouth of Guanica Bay, about 1.8 km from the mouth of the nearest river (Rio Loco; Fig. 1C). The Guanica site is immediately east of the Turrumote site (Fig. 1C), and also lies within the driest region of the island. The coastal ridge along the southwest coast that protects the Turrumote site from runoff forms an inland valley and diverts runoff from the Cordillera Central into the Rio Loco and its associated irrigation canals. The Rio Loco watershed drains the southern slopes of the Cordillera Central and the southern coastal plain, which is the largest active agricultural area in present-day Puerto Rico.

The third study site was located in the northeast corner of the island, 1.2 km from the mouth of the Fajardo River (Fig. 1D). Several smaller streams originating in the Luquillo Mountains feed the Fajardo River, which flows eastward, and drains into Vieques Sound. The Fajardo region lies on the windward side of Puerto Rico near the El Yunque sub-tropical rain forest, and receives an average of 1592 mm yr^{-1} in rainfall (Lugo and Garcia-Martino, 1996). This study region receives nearly double the annual rainfall compared to the southwest region of Puerto Rico (Lugo and Garcia-Martino, 1996), where the other two study sties were located.

Instrumental data about the study sites came from multiple sources. Local tropical cyclone histories were obtained for each site by determining the named storms that came within 92.6 km (50 nautical miles, nmi) from each study site using the Hurdat database (McAdie et al., 2009) and the National Oceanic and Atmospheric Administration (NOAA) Coastal Cervices Center online storm-track mapping tool. The cyclones were considered at any stage of their development from tropical depressions (TD) to category 5 hurricanes (Saffir-Simpson Scale (Saffir, 1977; Simpson and Riehl, 1981)). Discharge data for Rio Fajardo (USGS Station #50071000) and Rio Loco (USGS Station #50128905) were obtained from publicly available datasets collected and maintained by the U.S. Geological Survey (USGS). The precipitation data are from station data available through the NOAA National Climatic Data Center website at http://www.ncdc.noaa.gov/oa/ncdc.html.

2.2.2. Coral data

All three coral cores were collected from living *Montastraea faveolata* colonies growing at depths between 4 and 6 m. The cores were cut into slabs and x-radiographed at Nova Southeastern University. The resulting images were used to determine the growth chronology of each coral core by counting annual density-band couplets (Buddemeier and Kinzie, 1976; Knutson et al., 1972) and assuming that the high-density portion of each annual band formed in early summer (Watanabe et al., 2002). Subsamples for isotopic analysis were obtained by continuously drilling parallel to the primary growth axes, removing powders at 0.6 mm intervals in the Turrumote core (1993–2004), and at 1 mm intervals in the Guanica (1951–2004) and Fajardo (1948–2004) cores. Linear extension rates averaged 7.88 ± 1.51 mm yr^{-1}, 6.06 ± 0.80 mm yr^{-1}, and 5.72 ± 1.20 mm yr^{-1} for the Turrumote, Guanica, and Fajardo cores, respectively. Thus, each sample represents about

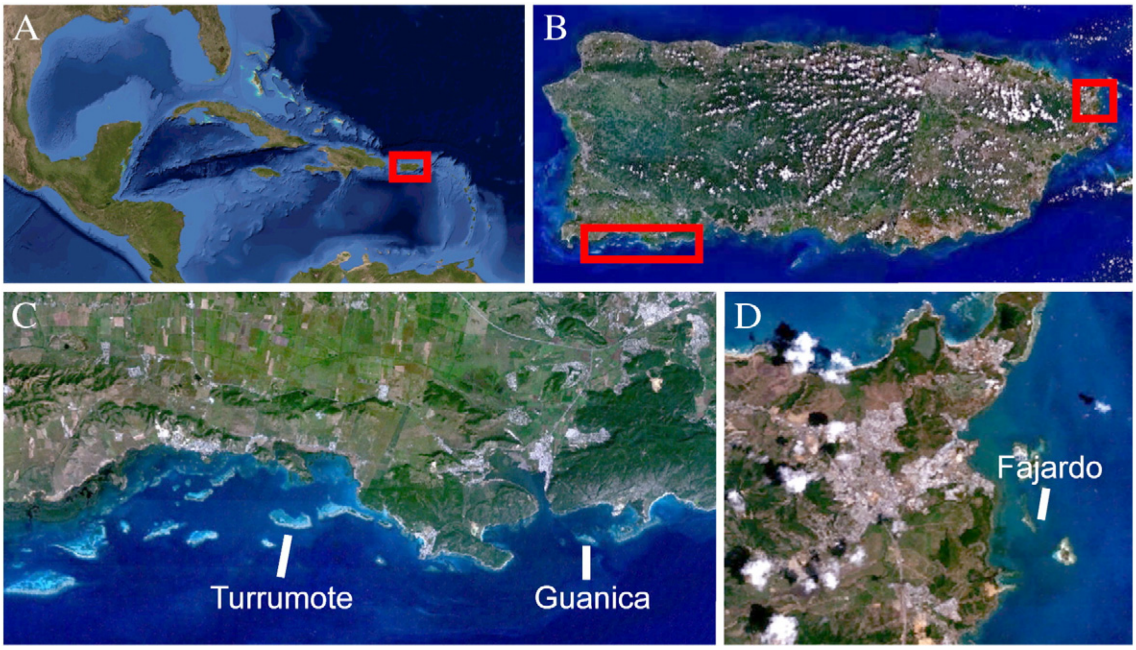

Fig. 1. Map showing A) the location of Puerto Rico in the Western Atlantic Ocean. The box indicates the location of Puerto Rico; B) The location of the study areas within Puerto Rico. Study areas are indicated by boxes; C) The locations of coral core collection for the Turrumote and Guanica coral cores; and D) The collection site of the Fajardo coral core. Base images are Landsat 7 mosaics available from http://www.nasa.gov.

1 month in the Turrumote core and 2 months in the Guanica and Fajardo cores.

We estimated that this sampling resolution would result in identifiable anomalies based on a simple calculation. A three day perturbation to −10‰ in a 60-day sample with an average $\delta^{18}O$ value of −4.5‰ the rest of the time will alter the mean value by 0.22%, well within the analytical precision, and therefore likely identifiable. To test if the monthly sampling in the coral records obscured any short-lived $\delta^{18}O_{sw}$ signals from a specific tropical cyclone event (Hurricane Georges, 1998), the Turrumote coral was re-sampled over the 1998–1999 density bands at a rate of 50 samples per year.

For each coral stable isotope sample, approximately 50–100 μg of skeletal powder was acidified at 70 °C with 100% H_3PO_4 in a Kiel carbonate auto-sampling device. The carbon and oxygen isotopic ratios of the resulting CO_2 gas were measured with a Finnigan stable isotope ratio mass spectrometer. Only $\delta^{18}O$ values are presented here and are reported as the per mil deviation of the ratio of $^{18}O/^{16}O$ relative to the Vienna Pee Dee Belemnite (VPDB) calcite standard (Coplen, 1996). Analyses of the Turrumote core were performed at the University of South Florida College of Marine Science Paleoclimate, Paleoceanography and Biogeochemistry Laboratory (PPB Lab). Analyses of the Fajardo and Guanica cores took place at Grottoli's Stable Isotope Biogeochemistry Laboratory. Precision (one standard deviation of the mean, σ) for replicates of standard material and duplicate samples was better than ±0.08‰ for $\delta^{18}O$ from both laboratories based on the long term PPB Lab precision on 6 NBS-19 calcite standards run with every 40 samples for the Turrumote core and 95 NBS-19 analyses for the Guanica and Fajardo cores.

Table 1
Coral core and collection site metadata.

Site name	Latitude	Longitude	Water depth	Coral record time interval
Turrumote	17°56.074′N	67°00.074′W	5 m	1993–2004
Guanica	17°56.531′N	66°53.568′W	4 m	1951–2004
Fajardo	18°19.413′N	65°37.084′W	6 m	1948–2004

Further description of the details regarding coral coring, laboratory sampling, and geochemical analyses are given in Kilbourne (2006), Kilbourne et al. (2008) and Moyer (2008).

2.2.3. Tropical cyclone event identification in coral skeletal records

Our approach was based on the premise that coral $\delta^{18}O$ is influenced by the normal seasonal cycles in temperature and seawater $\delta^{18}O$ as well as more sudden seawater $\delta^{18}O$ changes due to tropical cyclone events. The high frequency seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$) signal due to added precipitation was isolated by removing the seasonal signal, which is dominated by temperature (Kilbourne et al., 2008), from the coral $\delta^{18}O$ data in two ways. The Turrumote coral $\delta^{18}O$ record was used to reconstruct $\delta^{18}O_{sw}$ by removing the local seawater temperature record (Winter et al., 1998) using the methods of Gagan et al. (1998) with the Leder et al. (1996) calibration equation. Local temperature records were not available for the Guanica and Fajardo sites, so the short-term seawater $\delta^{18}O$ changes were isolated from these coral records by removing the average seasonal cycle from the detrended coral $\delta^{18}O$ data.

This has been shown to be as good as removing the temperature signal explicitly (Kilbourne et al., 2004) because the monthly temperature anomalies from the seasonal cycle are relatively small (standard deviation of 0.5 °C, translating to 0.1‰) compared to seawater $\delta^{18}O$ variability. In this location, temperature tends to dominate the seasonal cycle, while interannual variability is dominated by salinity-related seawater $\delta^{18}O$ variability (Kilbourne et al., 2008). Using an independent temperature proxy such as Sr/Ca under these climatic conditions would add unnecessary error to the results (Kilbourne et al., 2004), especially since interpreting Sr/Ca from *M. faveolata* can be problematic (Kilbourne et al. 2008). We confirmed the frequency-based temperature correction was equivalent to removing SST explicitly by applying both types of corrections to the Turrumote $\delta^{18}O$ data.

Four objective criteria were applied to each coral $\delta^{18}O$ anomaly time series in order to identify large negative $\delta^{18}O$ perturbations that potentially represented tropical cyclones. The resulting four event chronologies for each coral $\delta^{18}O$ record were then compared to the local tropical cyclone histories, local precipitation, and river discharge events to determine if the largest coral $\delta^{18}O$ anomalies were associated with tropical-cyclone-related rainfall and runoff. The following criteria were used: 1) coral $\delta^{18}O$ anomaly values that were 1.5 and 2 standard deviations below the mean of the entire coral $\delta^{18}O$ record were identified as tropical cyclones, and 2) values of the discrete first derivative of the coral $\delta^{18}O$ anomalies that were 1.5 and 2 standard deviations below the mean of the first derivative were identified as tropical cyclones. The first derivative was determined by subtracting the first value from the second value, then the second value from the third value, etc. The derivative-based criteria were used because tropical cyclone events should cause a rapid change in the composition of the seawater, either due to direct rainfall, or via large river discharge events. 1.5 and 2 standard deviation thresholds were used for comparison because the 2 standard deviation threshold would potentially identify large events but miss smaller events whereas the 1.5 standard deviation threshold would be more likely to accurately capture all tropical cyclone events but might also include non-tropical cyclone events.

Does the $\delta^{18}O$-based reconstruction correctly identify more past tropical events than expected from randomly assigning events to years based merely on the historic local tropical cyclone frequency? The chance of randomly choosing n years and having X tropical cyclones occur in those years can be described by a binomial distribution where the underlying probability p is equal to the likelihood of a tropical cyclone occurring in any one year. The probability of a tropical cyclone in any one year, p, was estimated based on the number of tropical cyclones within 50 nmi of each study site over the period during which we have coral $\delta^{18}O$ records: 18 storms in 56 years for Fajardo ($p=0.32$), and 10 storms in 52 years for Guanica ($p=0.19$). The null hypothesis in this case is that the probability of identifying a year when a tropical cyclone occurred is the same as the probability of a tropical cyclone occurring in the area in any given year. The alternative hypothesis is that the probability of identifying years with a tropical cyclone is greater than random. If the null hypothesis can be rejected (based on a 95% confidence level or <5% probability that the null hypothesis is true), then the reconstruction has skill beyond random guessing.

3. Results and discussion

3.1. Modeled seawater $\delta^{18}O$ response to rainfall

Seawater oxygen isotope ratio ($\delta^{18}O_{sw}$) measurements from southwestern Puerto Rico indicated a normal range of variation between 0.2‰ and 1.0‰ VSMOW (Fig. 2). Given a ±0.6 (2 σ) error in reconstructing $\delta^{18}O_{sw}$ from coral skeletal $\delta^{18}O$ (Kilbourne et al., 2008), reconstructed $\delta^{18}O_{sw}$ anomalies must be less than −0.4‰ (i.e., 0.2‰–0.6‰ = −0.4‰) or greater than 1.6‰ (i.e., 1.0‰ + 0.6‰ = 1.6‰) to be identified as detectably different from normal. The mixing model predicts that to get a $\delta^{18}O_{sw}$ value of at least −0.4‰, salinity would have to decrease to 33.0–30.5 psu depending on the isotopic composition of the rain (Fig. 2; Table 2). If the rain mixed 5 to 10 m deep, then it would take 29–131 cm of rainfall to obtain such salinity values. This amount of rainfall is not rare, but the largest rainfall amounts are usually recorded near the summits of Puerto Rico's Cordillera Central. Storm precipitation totals from NOAA stations around Puerto Rico indicate that tropical cyclone precipitation amounts have reached >29 cm 21 times since 1960 with the largest storm total reaching 106 cm (Tropical Depression 19A, 1970).

3.2. Coral-based tropical cyclone reconstructions from Puerto Rico

An 11.6-year $\delta^{18}O_{sw}$ reconstruction from the Turrumote coral skeletal $\delta^{18}O$ data is shown in Fig. 3A (Kilbourne et al., 2008). The reconstructed variability was well within the range of $\delta^{18}O_{sw}$ values previously measured offshore from La Parguera on the same reef complex where

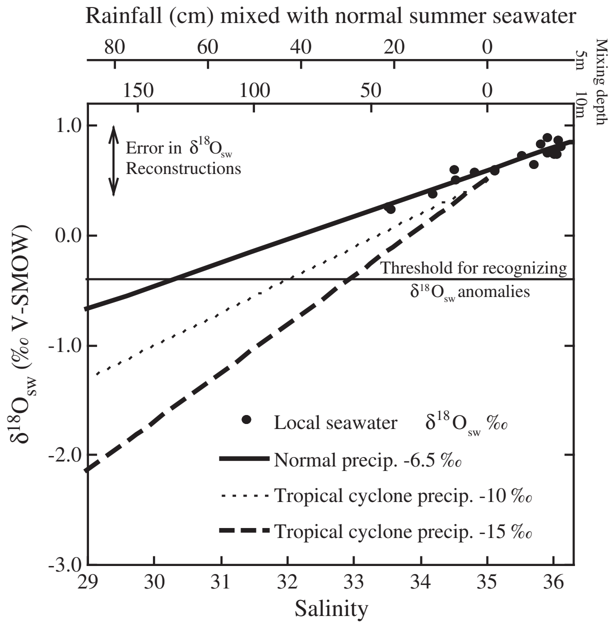

Fig. 2. Lines show the dependence of seawater oxygen isotope ratios ($\delta^{18}O_{sw}$) on salinity under conditions representing mixing between seawater and precipitation with three different $\delta^{18}O$ values. The amount of rainfall required for a given modeled salinity is shown on the top two axes, for rainfall mixing with ocean water columns of two different depths. Dots indicate paired measurements of $\delta^{18}O_{sw}$ and salinity taken from the reef offshore from La Parguera, Puerto Rico during all seasons over the course of a few years (Watanabe et al., 2002). The error bar represents the 95% confidence interval on coral-based $\delta^{18}O_{sw}$ reconstructions at this location (±0.6‰), including analytical error and calibration error (from Kilbourne et al., 2008). This forms the basis for the −0.4‰ threshold beyond which $\delta^{18}O_{sw}$ anomalies are considered significant.

the coral grew (Watanabe et al., 2002). Two tropical cyclones passed near the site during the study period, but neither was associated with a dramatic reconstructed negative $\delta^{18}O_{sw}$ anomaly (Fig. 3A). Rainfall from Hurricane Hortense (10 September 1996, category 1) focused over the northeast portion of the island, leaving southwestern Puerto Rico virtually dry. Hurricane Georges (21 September 1998, category 2) produced 23 cm of rainfall at the Lajas rain station (12 km inland from La Parguera). In addition, no dramatic negative $\delta^{18}O$ anomalies in the high-resolution Turrumote coral data corresponded with the passing of Hurricane Georges (Fig. 3B). Thus, as our model predicted, 23 cm of rainfall was not enough to produce a detectable signal.

The results from the Guanica (Fig. 4) and Fajardo (Fig. 5) sites were similar, and the data from the Fajardo site is discussed as an example. Precipitation, river discharge, coral $\delta^{18}O$ anomaly, and tropical cyclone data for the Fajardo site all demonstrated that the events identified using the objective reconstruction criteria rarely coincided with actual tropical cyclones that passed near the site (Fig. 5A and B). Based on the deviations in the Fajardo coral $\delta^{18}O$ anomalies, 9–23 tropical cyclones were identified over the study period (Table 3). However, these inferred cyclones rarely corresponded with actual

Table 2
The surface ocean salinity and amount of rain required to generate $\delta^{18}O_{sw}$ values lower than −0.4‰ for three different rainfall isotopic compositions.

Rain $\delta^{18}O$	−6.5‰	−10‰	−15‰
Salinity	30.5 psu	32.0 psu	33.0 psu
Rain mixed 5 m	74 cm	43 cm	29 cm
Rain mixed 10 m	131 cm	87 cm	57 cm

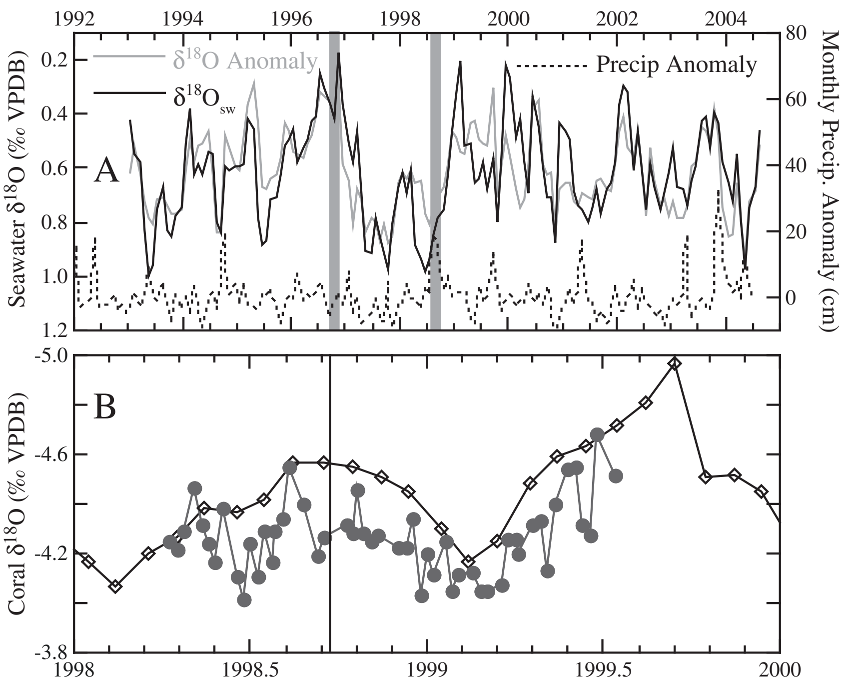

Fig. 3. A) Turrumote reef reconstructed seawater $\delta^{18}O$ (Gagan et al., 1998; Kilbourne et al., 2008) based on monthly coral $\delta^{18}O$ and local sea surface temperatures, and coral $\delta^{18}O$ anomalies plotted with monthly precipitation anomalies. The coral $\delta^{18}O$ anomalies have been shifted by 0.62 so they have the same mean as the reconstructed seawater $\delta^{18}O$. The precipitation data are derived by averaging the monthly totals of two stations (Lajas and Magueyes Island) from the NOAA National Data Center, and then subtracting the seasonal cycle of the combined record. Hurricanes Hortense (1996) and Georges (1998) are shown by gray bars. B) Monthly (diamonds) and weekly (circles) coral $\delta^{18}O$ from parallel paths of the same core. The single vertical bar represents the passage of Hurricane Georges.

cyclones that passed near Fajardo (Fig. 5B and C). Of the eighteen tropical cyclones that did pass near the Fajardo site during the study period, only four were correctly identified in the Fajardo coral reconstruction. Similarly, of the 10 tropical cyclones that passed by the Guanica site during the study period, no more than two were correctly identified by the coral reconstruction (Table 3).

The Guanica and Fajardo tropical cyclone reconstructions shown in Table 3 contained three types of reconstruction errors. One type of error occurred when tropical cyclones that passed over Puerto Rico were not identified in the reconstruction (omission errors). Another type of error occurred when tropical cyclone events were identified from the coral skeletal $\delta^{18}O$ data but there was no record of a tropical cyclone passing within 50 nmi (false positives). The third type of error was a different type of false positive and occurred when a storm was identified in a reconstruction and no storm passed within 50 nmi of the site, but the site was strongly affected by a storm that was further away. This type of error occurred in October of 1970 when TD 19A was in the area and the first derivative-based reconstructions from Fajardo indicate an event. TD 19A generated the largest monthly precipitation anomaly during the study period (Fig. 5A), but it was not originally identified as a storm that passed close to Fajardo because it did not reach named storm status. Neither false positives nor omission errors dominated, indicating that the poor results were due to both a lack of recording tropical cyclone signals and a tendency for the coral to exhibit strong $\delta^{18}O$ variations without the influence of a tropical cyclone.

The coral-based tropical cyclone reconstructions for the Fajardo and Guanica sites were similar to each other (Table 3). For each reconstruction, the null hypothesis (H_0) could not be rejected (Table 3). Thus, there was a high likelihood that we would get similar results if we randomly choose years to declare that there had been a tropical cyclone. The critical number of correct identifications needed to reject the H_0 ranged from 6 to 12, depending on the site and the number of actual tropical cyclone events.

3.3. Making accurate records of past tropical cyclones

The objective reconstruction criteria applied to coral $\delta^{18}O$ data from three different locations in Puerto Rico did not result in skillful tropical cyclone reconstructions. Multiple explanations for this result are reasonable. Below we discuss the following three requirements for successful tropical cyclone reconstructions as they pertain to our study: 1) a well characterized environmental signal exists, 2) the proxy records the signal, and 3) the signal is adequately recovered from the proxy.

3.3.1. Generating the signal

The mixing model presented here represents a first-order attempt to determine if a tropical cyclone can generate an isotopic signal in the coastal zone of Puerto Rico. Although the substantial isotopic depletion in tropical cyclone-related precipitation has been utilized for reconstructing tropical cyclone events from cave deposits (Frappier et al., 2007b), marine proxies present a more difficult problem because the ocean is an enormous reservoir of water that dilutes the meteoric water signal.

The results of our mixing model demonstrate that although a signal is possible in the shallow coastal zone, most tropical cyclones are not likely to produce enough rain over the ocean to create a signal. According to the model, a tropical cyclone with precipitation having a $\delta^{18}O$ value between −10 and −15‰ must produce between 43 and 29 cm of rainfall that mixes in only the top 5 m of the surface ocean to generate a $\delta^{18}O_{sw}$ signal that is beyond the normal variability in Puerto Rico (Table 2).

How much precipitation does a tropical cyclone produce in the coastal zone? Daily rainfall totals can provide an idea of the magnitude of rainfall during events. The largest daily rainfall total recorded for the Fajardo rain gauge between 1931 and 1996 was 26.2 cm. Despite the fact that stations at higher elevations regularly received more than our

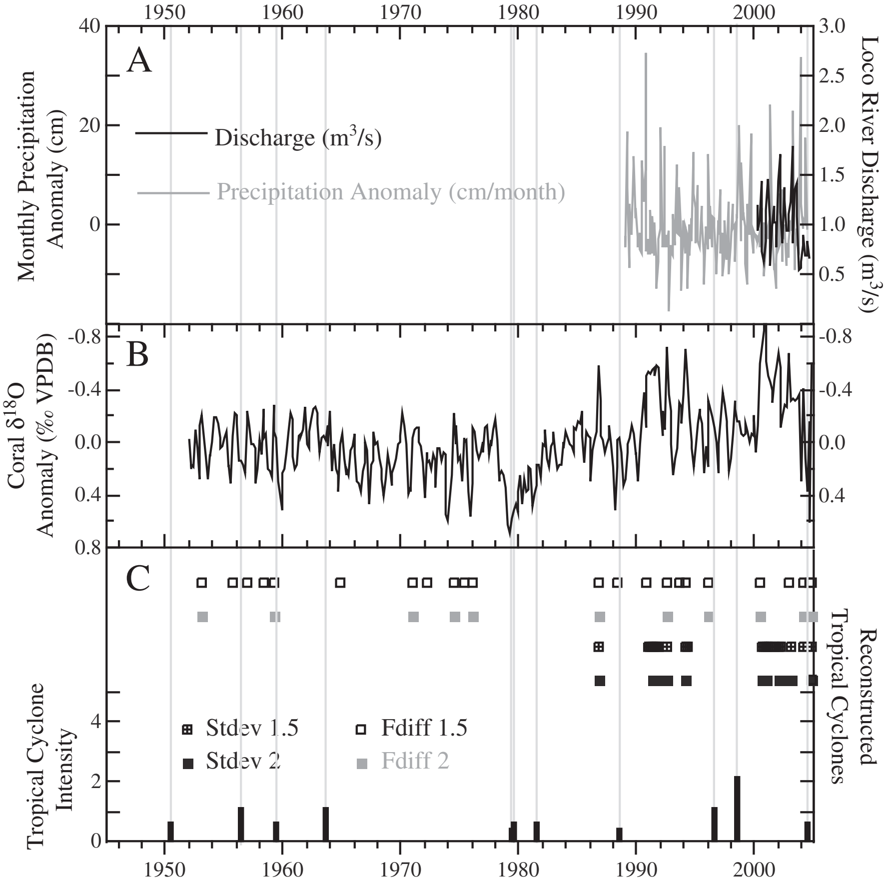

Fig. 4. Summary of data from the Guanica River site. Tropical cyclone events that passed within 50 nmi (92.6 km) of the site are represented by thin gray lines across all panels. A) Loco River discharge and monthly precipitation anomalies from station 665097(NOAA National Data Center). B) Coral skeletal $\delta^{18}O$ anomaly from the Guanica core. C) Tropical cyclone reconstructions (squares) based on the coral skeletal $\delta^{18}O$ data in B using the following 4 threshold criteria: 2 standard deviations from the mean of the $\delta^{18}O$ anomalies (black squares), 1.5 standard deviations from the mean of the $\delta^{18}O$ anomalies (hatched squares), 2 standard deviations from the mean of the $\delta^{18}O$ anomaly first differences (gray squares), and 1.5 standard deviations from the mean of the $\delta^{18}O$ anomaly first differences (outlined squares). The magnitudes of historical tropical cyclones are depicted as vertical bars where the height of the bar indicates the Saffir–Simpson scale intensity with tropical depressions plotted as 0.25 and tropical storms plotted as 0.5.

calculated 29 cm threshold, coastal sites tend to receive lower rainfall amounts. Thus precipitation alone cannot generate a large enough signal in the coastal ocean, and sites with significant riverine input of meteoric waters are more likely to have a signal. This can explain the lack of a tropical cyclone signal in the Turrumote coral, but does not explain the lack of tropical cyclone signals in the Fajardo and Guanica corals.

An important aspect of signal generation is determining what processes create a signal but the individual behavior of each tropical cyclone makes it difficult to generalize a canonical tropical cyclone signal. For example, slow moving tropical depressions that sit over an area for multiple days (such as TD 19A) are likely to generate larger signals than strong, fast moving storms. Rainfall totals can be helpful for exploring an expected signal, but the key factor is identifying the isotopic signal left by tropical cyclones. This requires measuring the magnitude and duration of the $\delta^{18}O_{sw}$ signal in the coastal zone after tropical cyclones strike.

Another important variable to measure is the sea surface temperature (SST) change in the coastal zone associated with the passing hurricane. Normally, the high heat capacity of the ocean keeps it from experiencing rapid temperature fluctuations that might interfere with a tropical cyclone signal in a coral. However, storms mix water deeply, creating cold wakes behind storms over the open ocean that can be on the order of 3 °C cooler than the surrounding ocean and last for a few days (Price 1981). Since carbonate $\delta^{18}O$ is inversely related to temperature, rapidly cooling SST would cause a positive anomaly in the carbonate (about +0.6‰ for a −3 °C anomaly), counteracting any negative anomaly caused by the precipitation and runoff. Approximately 20–30 cm of rainfall mixed into 5 m of water is required to reduce the salinity enough to counteract a −3 °C temperature anomaly; more rainfall is needed if it is mixed to deeper depths.

3.3.2. Recording the signal

Once the nature of the expected signal is established, the next step is to find a proxy that records the signal. This study focused on the coral species *Montastraea faveolata*, a common Caribbean reef coral and the species most widely used for paleoclimate reconstructions in the Atlantic basin. *Montastraea* spp. are known to be sensitive to tropical cyclone-related salinity changes (Goreau 1964), so it is possible that our specimens were not calcifying during or after the passage of tropical cyclones. This is one possible explanation why the Fajardo and Guanica coral records do not show a robust response to tropical cyclones in the area.

Siderastrea spp. tend to be the scleractinian coral that is least sensitive to disturbance by tropical cyclones (Goreau 1964), so they may be a better target for future attempts at reconstructing past tropical cyclone events. Maupin et al. (2008) showed that *Siderastrea siderea* can provide accurate paleoclimate records. However, *S. siderea* generally exhibits slower growth rates than *M. faveolata*, which raises concern over whether a colony will calcify enough during the passage of a tropical cyclone to record the event, and whether mm-scale coral subsampling can resolve the event given the slow growth rates. Faster

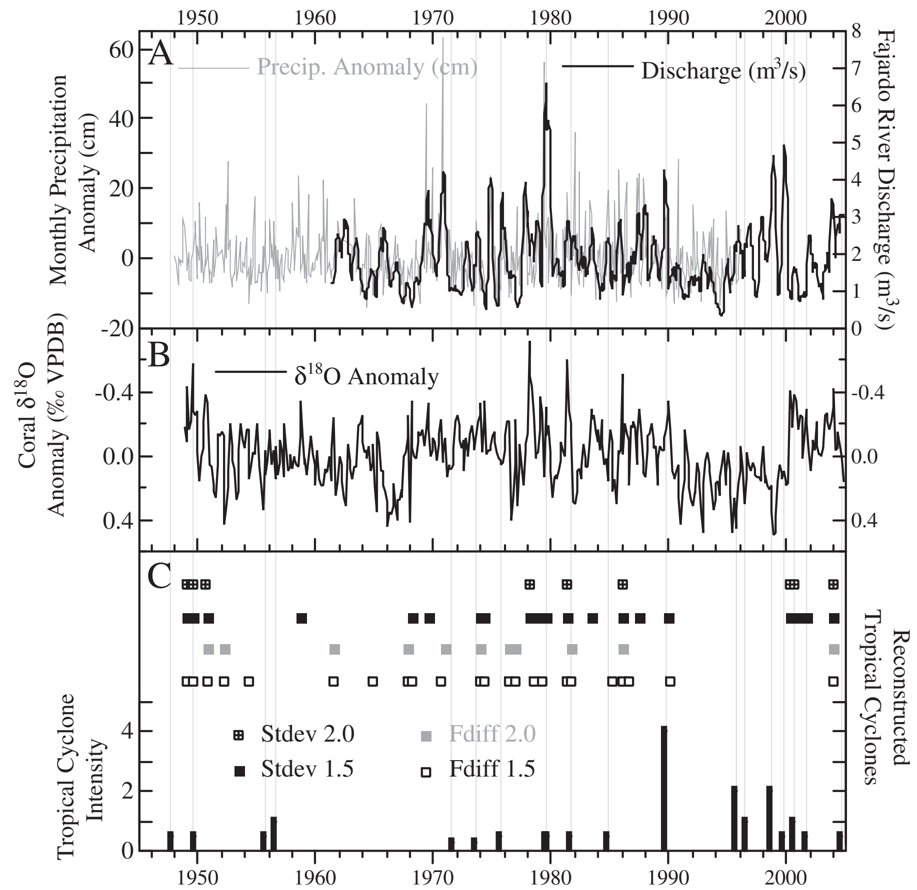

Fig. 5. Summary of data from the Fajardo River site. Tropical cyclone events that passed within 50 nmi (92.6 km) of the site are represented by thin gray lines across all panels. A) Fajardo River discharge and monthly precipitation anomalies from station 663657(NOAA National Data Center) show that tropical cyclone events at this site are not always accompanied by unusually heavy precipitation and runoff. B) Coral skeletal $\delta^{18}O$ anomaly from the Fajardo 3 core. C) Tropical cyclone reconstructions (squares) based on the coral skeletal $\delta^{18}O$ data in B using the following 4 threshold criteria: 2 standard deviations from the mean of the $\delta^{18}O$ anomalies (hatched squares), 1.5 standard deviations from the mean of the $\delta^{18}O$ anomalies (black squares), 2 standard deviations from the mean of the $\delta^{18}O$ anomaly first differences (gray squares), and 1.5 standard deviations from the mean of the $\delta^{18}O$ anomaly first differences (outlined squares). The magnitudes of historical tropical cyclones are depicted as vertical bars where the height of the bar indicates the Saffir–Simpson scale intensity with tropical depressions plotted as 0.25 and tropical storms plotted as 0.5.

growing organisms that are less sensitive to environmental perturbations should be targeted for future storm reconstructions because they are more likely to record tropical cyclone signals.

3.3.3. Recovering the signal

Time averaging can mute a short event signal such as that of a tropical cyclone. Monthly and weekly resolution samples from the Turrumote core, provide confidence that we did not see $\delta^{18}O$ depletions because either there was no environmental signal, or the coral did not record the environmental signal. Bi-monthly resolution sampling from the Fajardo and Guanica cores leaves open the possibility that the tropical cyclone reconstructions would have been more accurate with higher temporal resolution data. Whereas bi-monthly sampling for $\delta^{18}O$ has been shown to be sufficient for reconstructing seasonal and interannual variability (Quinn et al., 1996; Delong et al., 2007), it could be too coarse for resolving short-lived events. Further work is necessary to demonstrate the optimal sampling resolution for tropical cyclone reconstruction.

4. Conclusions

Although this initial attempt did not result in reliable coral-based reconstructions of tropical cyclone events, coral $\delta^{18}O$ cannot be discounted as a potential recorder of tropical cyclone events until more research has been conducted. Our results show that corals which are able to survive exposure to river runoff and sedimentation, could contain tropical cyclone-related $\delta^{18}O_{sw}$ signals, but that those signals need to be better understood, especially with respect to the physical characteristics (size, duration, rainfall, etc.) of individual storm events. Another

Table 3
Summary of the tropical cyclone reconstructions using coral skeletal $\delta^{18}O$ anomalies from sites near Fajardo and Guanica, Puerto Rico.

	Fajardo $\delta^{18}O$				Guanica $\delta^{18}O$			
	Stdev 1.5 σ	Stdev2 σ	First Diff. 1.5 σ	First Diff. 2 σ	Stdev 1.5 σ	Stdev 2 σ	First Diff. 1.5 σ	First Diff. 2 σ
Events identified	20	9	23	11	21	14	23	12
Correct identifications (% of events)	4 (20%)	2 (22%)	2 (9%)	1 (9%)	1 (5%)	1 (7%)	2 (9%)	1 (8%)
Omission errors	14	16	16	17	9	9	8	9
False positive errors	16	7	21	10	20	13	22	11
Prob. H_0 true	92.5%	83.9%	99.8%	98.6%	98.9%	95.0%	95.2%	92.3%

consideration is that the coral must continue to calcify while exposed to the stress of high turbidity and low salinity. The robust species *Siderastrea siderea* could be a better tropical cyclone recorder than the stress-sensitive *Montastraea faveolata* because of this. Finally, in order to recover a signal, it must be recorded in enough of the skeleton that it is not averaged out through mechanical sub-sampling of the coral skeleton. Choosing the correct balance between time resolution and costs to generate the record will be important for producing many records from many sites, necessary for characterizing basin-scale patterns of tropical cyclone activity on decadal and greater time scales.

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