Tracking interannual to multidecadal-scale climate variability in the Atlantic Warm Pool using central Caribbean coral data

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Key Points:

- Caribbean coral proxy records show stronger regional warming than grid-SST data and a drying trend over the past century
- Coral $\delta^{18}O$ tracks decadal and multidecadal North Atlantic Oscillation variability in the region of the Loop Current and Gulf Stream system
- Combined Caribbean coral proxy records provide SST information for large sparsely sampled Atlantic regions beyond the Caribbean

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Abstract

Atlantic Warm Pool (AWP) climate variability is subject to multiple influences of remote and local forcing. However, shortage of observational data before the mid-20th century and of long-term sea surface temperature (SST) and climate records has hampered the detection and investigation of decadal- and longer-scale variability. We present new seasonally resolved 125-year records of coral $\delta^{18}O$ and Sr/Ca variations in the Central Caribbean Sea (Little Cayman, Cayman Islands; Diploria strigosa). Both geochemical proxies show decreasing long-term trends, indicating long-term warming. Sr/Ca indicates much stronger regional warming than large-scale grid-SST data, while $\delta^{18}O$ tracks large-scale SST changes in the AWP. Seawater $\delta^{18}O$ variations are reconstructed, indicating a drying trend over the past century.

High spatial correlation between coral $\delta^{18}O$ and SST in the region of the Loop Current and Gulf Stream system suggests that Little Cayman is a sensitive location for detecting past large-scale temperature variability beyond the central Caribbean region. More specifically, our $\delta^{18}O$ data tracks changes in North Atlantic Oscillation (NAO) variability on decadal and multidecadal time scales providing insights into the temporal and spatial nonstationarity of the NAO. A combination of our $\delta^{18}O$ record with two coral records from different Caribbean sites reveals high spatial correspondence between coral $\delta^{18}O$ and SST variability in the North Atlantic subtropical gyre, where few instrumental measurements and proxies are available prior to the 20th century. Our results clearly demonstrate the potential of combining proxy data to provide information from sparsely sampled areas, helping to reduce uncertainty in model-based projections.

Introduction

Climate variability in the tropical Atlantic region produces numerous impacts on society and the environment of the surrounding continents on seasonal, interannual and multidecadal time scales through fluctuations in ocean and land temperature, rainfall and extreme events [*Moura and Shukla*, 1981; *Enfield and Alfaro*, 1999; *Giannini et al.*, 2000; *Hurrell et al.*, 2006]. Improving the assessment of the range of future climate fluctuations and their predictability relies on a better understanding of these fluctuations.

Unlike the tropical Pacific, the tropical Atlantic is dominated by the competing influence of modes of climate variability originating from tropical and extratropical oceans [*Sutton et al.*, 2000; *Marshall et al.*, 2001; *Czaja et al.*, 2002; *Czaja*, 2004; *Hurrell et al.*, 2006]. Interannual variability of north tropical Atlantic (NTA) climate is associated with the Pacific El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) [*Curtis and Hastenrath*, 1995; *Giannini et al.*, 2001a; *Giannini et al.*, 2001b; *Czaja et al.*, 2002; *Ruiz-Barradas et al.*, 2003; *Hurrell et al.*, 2006], both having significant teleconnections to the NTA. ENSO and NAO modulate the strength of the trade winds that affects SST through latent heat exchange at the ocean surface as well as the distribution and intensity of rainfall over the surrounding landmasses [*Enfield and Mayer*, 1997; *Giannini et al.*, 2000; *Giannini et al.*, 2001b; *Chiang*, 2002; *Czaja et al.*, 2002]. The relative importance of both modes for SST variability in the NTA appears to be frequency dependent, with ENSO dominating at interannual and the NAO at interdecadal time scales [*Czaja et al.*, 2002]. Both modes also influence SST variability in the Caribbean Sea which is linked to sea level pressure (SLP) variations in the North Atlantic region [*Hastenrath*, 1984] mainly through changes in surface winds which in turn affect the dynamics of the Atlantic Warm Pool (AWP) [*Wang et al.*, 2007; 2008b]. The AWP is a large body of warm water that comprises the Gulf of Mexico, the Caribbean Sea, and the western tropical North Atlantic. During its maximum extent in boreal summer, the AWP affects summer climate of the western Hemisphere [*Wang et al.*, 2006; *Wang et al.*, 2007] and can induce significant stress to Caribbean coral colonies during phases of sustained high temperatures as reported, e.g., in 1995, 1998, 2003, 2005, and 2009 [Ghiold and Smith, 1990; Coelho and Manfrino, 2007; Eakin et al., 2010; van Hooidonk et al., 2012]. As expected, the AWP fluctuates with the ENSO and NAO on interannual to decadal timescales [*Enfield et al.*, 2006], but also on the timescale of the Atlantic Multidecadal Oscillation (AMO)[*Wang et al.*, 2008a]. The AMO has been identified as the leading large-scale pattern of oscillatory changes in North Atlantic SST with a period of about 60-90 years [*Schlesinger and Ramankutty*, 1994; *Kerr*, 2000; *Enfield et al.*, 2001] over the last 150 years of instrumental observations. SST variations related to the AMO have been suggested to drive climate and precipitation patterns over regions including North America and the Caribbean [*Enfield et al.*, 2001; *Sutton and Hodson*, 2005; *Hu and Feng*, 2008] as well as tropical hurricane activity [*Goldenberg et al.*, 2001; *Hetzinger et al.*, 2008]. Ocean circulation in the Caribbean and Gulf of Mexico region of the AWP plays an important role in the heat transport from low to high latitudes. It is the source area of warm water masses leaving the low latitudes. The outflow via the Loop and Florida Current promotes the transequatorial heat transfer to higher latitudes through the Gulf Stream [*Schmitz and McCartney*, 1993; *Hogg and Johns*, 1995; *Sato and Rossby*, 1995; *Lund et al.*, 2006]. It is widely accepted that the Gulf Stream system is of fundamental importance to the climatic evolution in high northern latitudes and thus, to the living conditions in NW Europe. However, the lack of long-term SST and climate records has hampered the detection and investigation of variability and relationships between climate properties in the North Atlantic, especially on decadal and longer time scales [*Dommenget and Latif*, 2000]. Observational records are limited to the last 140 years and become sparser and spatiotemporally lacking before 1950 [*Smith and Reynolds*, 2003]. High-resolution climate proxy records from long-lived marine biota such as corals, bivalves and coralline algae can help to complement and significantly extend instrumental records back in space and time [*Jones et al.*, 2001; *Wanamaker et al.*, 2011; *Hetzinger et al.*, 2012; *Svendsen et al.*, 2014; *Zinke et al.*, 2014; *Hetzinger et al.*, 2016; *Sagar et al.*, 2016]. Additionally, these proxy records provide necessary input data for the calibration and validation of numerical climate models, which have the objective to enhance the understanding of internal variability in the coupled ocean-atmosphere system (e.g., the Northern Hemisphere ocean circulation, including the Caribbean Current, the Gulf Stream system, and the North Atlantic thermohaline circulation (THC) [*Latif et al.*, 2000; *Latif*, 2001; *Vellinga and Wu*, 2004]). An improved understanding of past variability of the climate system is also important with regard to long-range climate forecasting [*Delworth and Mann*, 2000], and to assess the anthropogenic impact on climate and ecosystems [*Delworth and Mann*, 2000; *Enfield and Cid-Serrano*, 2010; *Latif and Keenlyside*, 2011; *IPCC*, 2013].

Due to their long lifetime (up to several centuries) and rapid growth (typically more than 1 cm per year), corals can provide an ideal archive for the reconstruction of seasonal-to-multidecadal variability of environmental variables in the tropical surface oceans. Several studies have used geochemical proxies ($\delta^{18}O$ and Sr/Ca) as paleothermometers for the reconstruction of SSTs [*Smith et al.*, 1979; *Beck et al.*, 1992; *de Villiers et al.*, 1994; *Alibert and McCulloch*, 1997; *Gagan et al.*, 2000; *Marshall and McCulloch*, 2002; *Zinke et al.*, 2004; *Maupin et al.*, 2008; *DeLong et al.*, 2012]. Coral $\delta^{18}O$ is a combined signal of the temperature and the $\delta^{18}O$ of seawater, whereas coral Sr/Ca is primarily influenced by seawater temperature [*Smith et al.*, 1979].

This study presents a 125-year record of coral $\delta^{18}O$ and Sr/Ca variations from a *Diploria* *strigosa* coral drilled off Little Cayman (Cayman Islands, Central Caribbean Sea). We compare geochemical variations of the coral record with observational data and climate indices as well as other Caribbean coral records over the past 125 years to address questions including: (1) do the coral proxies record local and/or regional climate variability (i.e. SST and the hydrological cycle) and trends in long-term climate evolution? (2) Do the coral proxies capture impacts of major climate modes onto the Caribbean? (3) Does the geochemical record show the potential to track climate variability on large spatial scales, e.g. within the AWP region and the Gulf Stream system? (4) If so, how does the coral proxy record compare to other Caribbean coral records in terms of their references to possibly different regions and do they complement each other?

Materials and Methods

The most recent 42 years of Sr/Ca variations from this Little Cayman coral record were already examined in an earlier study by *von Reumont et al.* [2016] who compared this fore reef record to a record from the adjacent lagoon environment. Here, a new $\delta^{18}O$ and extended Sr/Ca record is presented: core LC3 spans 125 years, from 1887 to 2011.

2.1 Setting of the Study Area

Little Cayman is the smallest and least developed island of the three Cayman Islands with a human population of less than 200. It is 17 km long and from little more than a kilometre to 3 km wide. With the highest point 13 m above sea level it is a very flat island. The marine environment is characterized by an almost continuously developed fringing reef. Little Cayman is situated in the central Caribbean Sea, where it is sheltered by Cuba and Hispaniola from substantial wave input from the Atlantic. However, it is in a position to receive the full impact of a moderately strong unidirectional trade wind and wave field. Freshwater is scarce and the island lacks rivers and streams. Land based discharge of erosional products into lagoonal waters seems to be insignificant. More than 50% of the nearshore waters are designated as marine park or no-take zone, ensuring minimal direct anthropogenic stress. Little Cayman is bathed in waters of the Caribbean Current, the main surface current in the Caribbean Sea [*Wüst*, 1964; *Gordon*, 1967; *Hernandez-Guerra and Joyce*, 2000]. The island's climate is strongly moderated by the sea since no major land masses are present within a radius of 200 km. Overall Caribbean Sea climate, surface current patterns, and hydrography are subject to seasonal fluctuations, which are mainly controlled by the covarying pattern of trade wind convergence [*Hastenrath*, 1976; 1984], the seasonally northward and southward migration of the Intertropical Convergence Zone (ITCZ), and the underlying cross-equatorial SST gradient [*Carton et al.*, 1996].

2.2 Coral sampling

In July 2012 coral core LC3 was extracted from a hemispherical colony of *Diploria strigosa* on the north central coast of Little Cayman (19.7°N, 80.06°W). The colony had a diameter of 0.8 m and grew in a water depth of 9 m in the fore reef 200 m off the fringing reef. The core was drilled vertically approximately parallel to the central growth axis of the colony. The pneumatic drill was equipped with a 3.6 cm diameter core drill. Core LC3 has a length of 69 cm. The core was sectioned longitudinally into 7 mm thick slabs. The coral slabs were x-rayed (Figure S1) in order to expose annual density band couplets. A preliminary chronology was generated by counting the annual density bands. Core LC3 extends continuously from 1887 to 2011. The skeletal extension rate measured from the annual density bands averages 5.07 mm year^{-1} (±0.84 mm). Core LC3 was drilled as part of a field campaign during which the recovery of only one coral record from each part of the reef (lagoon, fore reef etc.) was permitted by the local environmental authority, making replication with several cores impossible.

2.3 Coral $\delta^{18}O$ and Sr/Ca

Powdered samples were collected for stable isotope and trace element analysis using a low-speed micro drill with a diamond-coated 0.5 mm diameter drill bit. The samples where drilled every 0.5 mm along the corallite walls (parallel to the growth axis), yielding on average 10 samples per year. Since the longitudinal axis of our core was slightly inclined to the growth axis of the coral, it was necessary to track jump downcore to stay in the growth axis. The molar Sr/Ca ratios were determined by inductively coupled plasma optical emission spectrometry (ICP-OES, Spectro Ciros SOP) at the University of Kiel. Element emission signals were simultaneously collected and subsequently drift corrected by sample-standard bracketing every five samples following a combination of technics described by *Schrag* [1999] and *de Villiers et al.* [2002]. Analytical precision on Sr/Ca determinations was 0.15% RSD or 0.01 mmol mol^{-1} (1σ) (n = 1350). The average Sr/Ca value of the JCp-1 standard [*Hathorne et al.*, 2013] from multiple measurements on the same day and on consecutive days was 8.855 mmol mol^{-1} with a RSD of 0.09%.
Oxygen isotope measurements were conducted on a Thermo Scientific MAT-253 mass spectrometer equipped with a CARBO Kiel IV device. The isotopic ratios are reported in ‰ relative to the Vienna Pee Dee Belemnite (VPDB) based on calibration directly to NBS-19 standard (National Bureau of Standards). Analytical uncertainty on $\delta^{18}O$ determinations was 0.06‰ (1σ) (n = 1350; 2 standards after every 10 samples).

2.4 Coral chronology

The coral chronology was developed based on the pronounced seasonal cycle in the Sr/Ca record. The maximum (minimum) Sr/Ca value was tied to February (September) of any given year, which on average is the coldest (warmest) month in the study area. Coral $\delta^{18}O$ and Sr/Ca time series were linearly interpolated between these anchor points using the Analyseries software [Paillard et al., 1996] to obtain age assignments for all other measurements. This approach creates a non-cumulative error of 1–2 months in any given year due to interannual differences in the exact timing of maximum (minimum) SST.

2.5 In-situ and gridded temperature data

In-situ water temperature data for Little Cayman Island is available from the Coral Reef Early Warning System (CREWS) station located within the fore reef zone < 400 m apart from coral colony LC3. The station is part of the Integrated Coral Observing Network (ICON) of the National Oceanic and Atmospheric Administration (NOAA). Hourly water temperatures were recorded by an NXIC-CTD (Conductivity, Temperature, Depth) from Falmouth Scientific at a depth of approx. 5 m. The employed dataset comprises three years of measurements. The record starts in August 2009 when the station was newly brought into service and ends in October 2012 due to storm damage three months after retrieval of the coral core. Monthly SST data for the calibration of the proxy records were extracted from the HadISST1 data set for the 1° × 1° grid box centered on 19.5°N and 79.5°W, including the coral site [Rayner et al., 2003]. These data were adjusted using an ordinary least squares (OLS) regression relationship between the HadISST and the CREWS data to create an augmented SST data set (referred to as such hereafter) [*von Reumont et al.*, 2016]. Augmented SST variability agrees very well with the local in-situ SST data set (r = 0.98) over the interval from 2009 to 2012.

Results and Discussion

3.1 $\delta^{18}O$ and Sr/Ca Records

The time series of monthly $\delta^{18}O$ and Sr/Ca variations extend from 1887 to 2011 and show clear seasonal cycles. The seasonality in monthly $\delta^{18}O$ has a mean amplitude of 0.27 ‰ while in monthly Sr/Ca it is 0.09 mmol mol^{-1}. The two time series correlate significantly over the entire length on the monthly ($r = 0.63$; $p < 0.0001$) and on the mean annual scale ($r = 0.62$; $p < 0.0001$).

Regressions of monthly $\delta^{18}O$ and Sr/Ca with augmented SST yield significant relationships for both proxies ($r = -0.54$ and -0.56, $\delta^{18}O$ and Sr/Ca respectively; $p < 0.0001$) (Table 1). Annual mean proxy values also correlate well with gridded SST ($r = -0.56$ and -0.54, $\delta^{18}O$ and Sr/Ca respectively; $p < 0.0001$). The resulting regression slopes show notable differences depending on temporal resolution. At monthly resolution regression slopes for $\delta^{18}O$ and Sr/Ca are -0.082(±0.003) ‰ °C^{-1} and -0.021(±0.001) mmol mol^{-1} °C^{-1} respectively, while at annual resolution they are clearly larger with -0.292(±0.039) ‰ °C^{-1} and -0.069 (±0.012) mmol mol^{-1} °C^{-1}. Slopes for published equations relating $\delta^{18}O$ and Sr/Ca from different tropical Atlantic coral genera to SST range from -0.101 to -0.22 ‰ °C^{-1} [*Leder et al.*, 1996; *Smith et al.*, 2006; *Maupin et al.*, 2008] and from -0.023 to -0.084 mmol mol^{-1} °C^{-1} [*Swart et al.*, 2002; *Cohen et al.*, 2004; *Goodkin et al.*, 2005; *Smith et al.*, 2006; *Maupin et al.*, 2008; *DeLong et al.*, 2011; *Xu et al.*, 2015] respectively. Previously published slopes for modern Caribbean *Diploria strigosa* [*Hetzinger et al.*, 2006a; *Giry et al.*, 2012; *Xu et al.*, 2015] range from -0.184 to -0.196 ‰ °C^{-1} for $\delta^{18}O$-SST and from -0.034 to -0.063 mmol mol^{-1} °C^{-1} for Sr/Ca-SST relationships. Compared with the published data our coral $\delta^{18}O$-SST and Sr/Ca-SST slopes of the monthly data are in the lower range while those of the annual data are in the higher range of slope values. Basic statistics of the calibrated proxy records in comparison to gridded SST are given in Table 2.

3.2 Long-Term Trends

Both geochemical proxy records show a pronounced centennial scale trend of decreasing $\delta^{18}O$ and Sr/Ca values over the time period from 1887 to 2011 (Figure 1a, b). The trend in Sr/Ca is equivalent to a warming of 1.60 °C whereas in $\delta^{18}O$ it is 1.06 °C (Table 3) if interpreted completely in terms of temperature (using the slope of the regression equations). However, in contrast to Sr/Ca, $\delta^{18}O$ variability is not only influenced by water temperature but also by seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$), which primarily reflects the regional precipitation-evaporation balance [*Zinke et al.*, 2008] and might account for the discrepancy in the magnitude of the temperature trends. Compared to the proxy records the $HadISST_{aug}$ data show a weaker warming of 0.62 °C which is in the lower portion of globally averaged surface temperature data analyzed by the *IPCC* [2013] that indicate a warming of 0.65 to 1.06 °C over the period 1880 to 2012. Warming calculated from $\delta^{18}O$ matches the upper IPCC warming estimate. Similar results, i.e. stronger proxy-derived warming trends than indicated by gridded SST data, have also been found in other coral-based SST reconstructions from this region. For example, coral proxy data from Puerto Rico [*Kilbourne et al.*, 2008] and Guadeloupe [*Hetzinger et al.*, 2010] yield temperature trends that are also up to two times larger than what the corresponding grid SST data suggest (Table 3). Such records not only have been found in corals but also in sclerosponges from Jamaica [*Rosenheim et al.*, 2005] and the Bahamas [*Rosenheim et al.*, 2004]. However, there are exceptions to these records from the Florida Keys [*Maupin et al.*, 2008; *DeLong et al.*, 2014] where coral records do not match this larger trend. In context of the larger trend, recently published observations from Little Cayman suggest that grid-SSTs, which are averaged over a large area and often

computed from multiple data sources [*Smith and Reynolds*, 2003], do not sufficiently represent local SST variability within the reef system from which the coral cores and thus the geochemical records have been retrieved [*von Reumont et al.*, 2016]. Furthermore, *Hetzinger et al.* [2010] showed that temperature trends derived from the coral Sr/Ca data of Guadeloupe *Diploria strigosa* are clearly consistent with those of local air temperature measurements starting in 1951 while grid-SST shows no warming in the same time period. The magnitude of the trend in Little Cayman Sr/Ca derived temperature is consistent with the observed increase in temperature at the other two Caribbean coral sites. This consistency indicates that the annual mean Sr/Ca values from our Little Cayman coral record yield a robust warming signal that is much stronger than suggested by large-scale grid-SST data, but of similar magnitude as other coral-derived proxy reconstructions. These trends in the coral temperature reconstructions together with the aforementioned coral records from the Florida Keys support the findings of a study of decadal SST trends (1985-2009) that includes the Caribbean Sea and the south-eastern Gulf of Mexico and uses Advanced Very High Resolution Radiometer (AVHRR) [*Chollett et al.*, 2012]. According to the AVHRR data the region of the Caribbean records is warming whereas the south-eastern Gulf of Mexico including the Florida Keys is not warming as quickly. One possible explanation of the spatial heterogeneity is reduced transport of warm water from the Caribbean into the Gulf of Mexico, at least on centennial time scales [*Lund et al.*, 2006], which may be further linked to reduced AMOC transport as suggested in a high-resolution simulation study by *Liu et al.* [2012]. However, this is not an explanation for the larger proxy-derived warming trends, which need to be further investigated by means of additional high-resolution proxy records and model simulations.
The comparison of the proxy results suggest that Sr/Ca is a better indicator of local changes in temperature, while δ^{18}O seems to be a better indicator of large-scale/regional scale SST changes. At the seasonal scale this assumption is corroborated by a good agreement of the seasonal cycle range between the gridded SST and δ^{18}O-SST, whereas Sr/Ca-SST shows a clearly larger range (Table 2). Furthermore, the monthly Sr/Ca record shows a distinct positive excursion around the years 1955-56 (Figure 1b). This suggests a cooling event, which coincides with the timing of a moderate La Niña event (-1.46) according to the Oceanic Niño Index (ONI, 1950-present), which measures departures from average SST in the Pacific Nino3.4 region. On the other hand δ^{18}O and SST show no deviation from general interannual variability at that time. The reasons for this singular Sr/Ca excursion cannot be completely determined here and may be due to several different factors related either to the coral proxy itself or to local variability. However, diagenetic alteration, which has been observed in some modern corals (e.g., *Porites*) [*Hendy et al.*, 2007; *Sayani et al.*, 2011], is not considered to be the cause. The skeletal mesoarchitecture of large-polyped *Diploria strigosa* facilitates microsampling that strictly follows a single skeletal element, the solid and thick theca wall. Different to the sampling in small-polyped corals such as *Porites*, sampling does not integrate over different skeletal elements and vacated skeleton where secondary aragonite infilling may occur. Here, microsampling was constrained to the central part of the theca, where the admixture of secondary cements, if present somewhere in the skeletal structure, is unlikely. Additionally, no indications of secondary aragonite overgrowth were found in X-ray images of the core slabs that could point to diagenetic alteration effects. Although a singular feature, the Sr/Ca excursion potentially is a true local temperature signal that points to the higher sensitivity of Sr/Ca towards local SST changes compared to the δ^{18}O signal.

In addition to trends in both proxy records with a focus on SST, we investigate long-term changes in the hydrologic balance by using paired coral δ^{18}O and Sr/Ca measurements to calculate changes in seawater δ^{18}O ($\delta^{18}O_{sw}$). Several studies have demonstrated that past

$\delta^{18}O_{sw}$ variations can be reconstructed by removing the temperature component of the $\delta^{18}O$ signal by using Sr/Ca derived temperature [*McCulloch et al.*, 1994; *Gagan et al.*, 1998; *Ren et al.*, 2002; *Kilbourne et al.*, 2004; *Cahyarini et al.*, 2014]. We calculate relative changes in annual $\delta^{18}O_{sw}$ following the method described in *Cahyarini et al.* [2008], assuming a coral $\delta^{18}O$-SST relationship of -0.29 ‰ °C^{-1} and a coral Sr/Ca-SST relationship of -0.069 mmol mol^{-1} °C^{-1} based on our calibrations. Variations in $\delta^{18}O_{sw}$ are defined relative to the mean value of $\delta^{18}O_{sw}$ and are given as $\Delta\delta^{18}O_{sw\text{-}center}$ [*Cahyarini et al.*, 2009] (Figure 1d). Given the positive long-term trend in proxy derived temperatures total precipitation is expected to increase in conjunction with increasing tropical temperature since, in theory, increased heating leads to greater evaporation and thus higher precipitation [*Mitchell et al.*, 1987]. The long-term perspective on the $\Delta\delta^{18}O_{sw\text{-}center}$ data is inconsistent with this assumption. At our study site generally increasing $\Delta\delta^{18}O_{sw\text{-}center}$ suggests an overall reduction in precipitation from 1887 to 2011. However, the $\Delta\delta^{18}O_{sw\text{-}center}$ signal does not evolve in a linear way. From the beginning of the record until the mid-1970s the $\Delta\delta^{18}O_{sw\text{-}center}$ data shows a high inverse correlation with the AMO, ($r = -0.88$; $p < 0.0001$) [*van Oldenborgh et al.*, 2009] (Figure 1d), thus being consistent with the above assumption that when temperature increases precipitation increases and vice versa. Starting in the mid-1970s the $\Delta\delta^{18}O_{sw\text{-}center}$ record seems to decouple from the AMO signal and shifts to a steadily increasing regime, i.e. precipitation decreases while temperature increases. Gauge data from the Global Historical Climatology Network (GHCN) data set (National Climatic Data Center (NCDC) summarized by *Trenberth et al.* [2007] showed that for the period from 1979 to 2005 precipitation patterns have developed such that the higher latitudes have become wetter and the subtropics and much of the tropics including the central Caribbean region have indeed become drier. Alterations in atmospheric circulation are associated with these patterns [*Trenberth et al.*, 2007], namely increases in the westerly winds at mid-latitudes and a strengthening of the northeasterly trade winds [*Kalnay et al.*, 1996]. These alterations should theoretically cause more evaporation and advection of moisture from the region, thereby increasing the $\Delta\delta^{18}O_{sw\text{-}center}$. A combination of higher evaporation and increasing temperature, as captured by our coral, could have negative long-term consequences on the Cayman Islands and similar low-lying islands with few fresh water resources. Empirical evidence and climate model simulations indicate that warmer climates, owing to increased water vapor, lead to more intense precipitation events, even when the total annual precipitation is reduced [*Trenberth et al.*, 2003; *Allan and Soden*, 2008]. Additionally more atmospheric moisture is available for tropical storms to feed upon [*Bender et al.*, 2010]. These factors often occur together, thereby increasing the potential incidence and severity of flooding events [*Trenberth*, 2011]. The warming on the other hand accelerates drying of land surfaces as the evaporation of moisture takes in heat, eventually leading to an increased risk of extended dry or even drought periods [*Dai et al.*, 2004].

Interestingly, while we observe a strong relationship between $\Delta\delta^{18}O_{sw\text{-}center}$ and AMO, this does not hold true for the individual $\delta^{18}O$ and Sr/Ca records. *Hetzinger et al.* [2008] and *Kilbourne et al.* [2008] have found a strong relationship between coral $\delta^{18}O$ and AMO in their records from Guadeloupe and Puerto Rico. However, these records come from locations in the southern and eastern Caribbean. Spatial distribution of correlations between annual mean SST and the AMO index over the time period from 1887 to 2011 shows that Guadeloupe and Puerto Rico are situated within a field of significant agreement (Figure S2). In contrast, no correlation exists in the northwestern part of the Caribbean, north of the latitude of Jamaica where the Cayman Islands are situated. The high correlation between our coral $\delta^{18}O$ and Sr/Ca records indicates a dominant role of SST in coral $\delta^{18}O$ variability at Little Cayman and consequently both proxy records show no significant relationship to AMO. Observational and model data provide evidence for a major role of atmospheric processes in generating the tropical portion of AMO variability [*Brown et al.*, 2016; *Yuan et al.*, 2016]. Observational analyses suggest that the focus of North Atlantic SST anomalies is in the midlatitudes during the mature stage of AMO and SST anomalies subsequently propagate into the tropics [Guan and Nigam, 2009; Kavvada et al., 2013; Hodson et al., 2014]. In response to a warm middle latitude SST anomaly tropical trade wind speed weakens which in turn reduces evaporation in the tropics Chiang and Friedman, 2012] [Qu et al., 2014]. This AMO related atmospheric effect on the hydrological balance might be an explanation for the observed coral $\delta^{18}O_{sw}$ signal with no necessary causal connection to local SST.

Hetzinger et al. [2008] could also show that their estimate of $\delta^{18}O_{sw}$ contribution to the $\delta^{18}O$ signal and precipitation are highly correlated at low frequencies to the AMO, implying that multidecadal $\delta^{18}O_{sw}$ variations in Guadeloupe are primarily atmosphere-driven. Presumably this observation applies to a wider region and perhaps also to the Puerto Rico and Little Cayman site.

3.3 Regional to Large Scale Variability

Spatial distribution of correlations between annual mean Sr/Ca and SST exhibit strong relations mainly restricted to the local level and not on regional to large scales (Figure S3). In contrast annual mean coral $\delta^{18}O$ reveals strong negative relations to SST in the eastern Sargasso Sea, but especially to SST in the Loop Current region (SST_{LC}) (Figure 2), where the clockwise surface flow extends northward into the Gulf of Mexico and joins the Yucatan Current and Florida Current. Strong correlations of coral $\delta^{18}O$ are also found to SST in the Gulf Stream region (SST_{GS}) upstream of Cape Hatteras, where the Florida Current ceases to follow the continental shelf. Our observation is consistent with results from *Hetzinger et al.* [2010] who found that $\delta^{18}O$ appears to be a better indicator of large scale SST variability in the tropical North Atlantic, while Sr/Ca appears to be a better indicator of local temperature variability. Consequently we focus on $\delta^{18}O$ variability for the investigation of regional to large scale SST variability. The observed relationships between $\delta^{18}O$ and SST_{LC} / SST_{GS} potentially make our study site a sensitive location for the detection of past regional scale variability within the Gulf Stream System. To validate/verify this assumption we determine one comparative grid-SST cell from the field with the strongest correlation for the Loop Current region and the Gulf Stream region, respectively. Figure 3 confirms that interannual variations in coral $\delta^{18}O$ agree very well with SST from the two selected regions. Both coral $\delta^{18}O$ and SST show a clear multidecadal variation with a period of ~80 yr. However, phase and thus period of the variation differs from AMO variability. A comparison of low-pass filtered data yields strong negative relationships between $\delta^{18}O$ and both SST time series from 1887 to the mid-1970s (Gulf Stream: $r = -0.98$; Loop Current: $r = -0.96$; $p < 0.0001$). Between the mid-1970s and 1990s the $\delta^{18}O$ signal is characterized by a departure from decreasing SST signals. This coincides with the behavior of $\Delta\delta^{18}O_{sw\text{-}center}$, which contributes to the $\delta^{18}O$ signal. During this time period three strong (> +1.5 °C; 1972-73, 1986-87, 1991-92) and two very strong (> +2.0 °C; 1982-83, 1997-98) El Niño events developed according to the ONI. Together with the 2015-16 El Niño the 1982-83 and 1997-98 events are the strongest on the ONI record, covering the period from 1950 to now. The El Niño Southern-Oscillation (ENSO) originates in the tropical Pacific Ocean but is known to exert a strong influence on climate variability in the northern tropical Atlantic and the Caribbean region [*Curtis and Hastenrath*, 1995; *Enfield and Mayer*, 1997; *Giannini et al.*, 2000; *Saravanan and Chang*, 2000; *George and Saunders*, 2001; *Giannini et al.*, 2001a; *Giannini et al.*, 2001b; *Czaja et al.*, 2002]. A spatial correlation of the ONI record with HadISST data over the time period from 1970 to 2000 (Figure S4) yields moderate values ($0.4 \leq r \leq 0.6$, $p < 0.1$) for the northeast Caribbean while for the Gulf Stream and Loop Current region no or only weak correlations can be observed ($0 \leq r \leq 0.2$, $p < 0.1$). Consequently we assume that ENSO can have a measurable impact on local SST and thus coral $\delta^{18}O$ at Little Cayman, which already has been shown for corals from other Caribbean sites [*Smith et al.*, 2006; *Maupin et al.*, 2008], while SST in the comparative regions seems to be unaffected. The frequency and magnitude of El Niño events likely has contributed to the $\delta^{18}O$ signal remaining at low values at Little Cayman compared to decreasing SSTs in the Gulf Stream and Loop Current region in Figure 3. Another prominent mode of external forcing on northern tropical Atlantic climate variability is the North Atlantic Oscillation (NAO) [*Czaja et al.*, 2002]. The NAO is associated with basin-wide variations in atmospheric circulation [*Hurrell*, 1995], which in turn result in changes in the regional distribution of temperature and rainfall over the North Atlantic and surrounding continents (including the Caribbean) [*Walker and Bliss*, 1932; *van Loon and Rogers*, 1978; *Rogers and Van Loon*, 1979]. We investigate the relationship between coral $\delta^{18}O$ and the two modes of climate variability, ENSO and NAO, to eventually identify forcing of corresponding variability between $\delta^{18}O$ at Little Cayman and SST in the Gulf Stream and Loop Current region. In order to do this, we perform wavelet coherence (WTC) analyses, which find regions in time frequency space where two time series co-vary (but do not necessarily have high power) [*Grinsted et al.*, 2004]. Results from WTC between coral $\delta^{18}O$ and the Nino3.4 index show only one significant ($p \leq 0.05$) field of covariance (Figure S5), which appears on interannual time scales with a period between 1 and 2 years around 1900. Elevated but insignificant values of annual to interannual covariation can be observed from 1940 into the 1990s comprising the time period of higher El Niño activity between the mid-1970s and 1990s considered above. While the ENSO systems effect on annual $\delta^{18}O$ is generally insignificant an examination of NAO variability gives a different picture. Strong and persisting covariation between $\delta^{18}O$ and NAO exists on decadal time scales in a band between 1920 and 1980 with periods around 12-16 years (Figure 4). This significant region is surrounded by elevated but insignificant values even reaching from around 1900 to around 2000. After 1980 into the 1990s significant covariation seems to switch to shorter, interannual periods between around 8-11 and 5-6 years. Additionally, we compute WTCs between annual $\delta^{18}O$ and SST_{GS} and SST_{LC} respectively (Figure 4), to investigate whether the two SST time series share time frequency patterns with $\delta^{18}O$ that also exist between $\delta^{18}O$ and NAO. Covariation in periods around 12-16 years is also present in both WTCs although not to similar extent. Both share a region of significant covariation between around 1940 and 1960 although covariation between $\delta^{18}O$ and SST_{GS} lasts longer, until around 2000. If elevated but not significant values are included, covariation between $\delta^{18}O$ and SST_{GS} coincides primarily with the region from 1900 and 2000 observed in the WTC between $\delta^{18}O$ and NAO. In contrast, covariation between $\delta^{18}O$ and SST_{LC} shows a narrower region on decadal scales, with no covariation existing before 1920 and after 1990. Here, the shift to shorter, interannual periods around the 1980s, as observed in WTC between $\delta^{18}O$ and NAO, also exists. The pattern of decadal variation is the dominant feature in all WTCs. This corresponds very well to results of *Hurrell and van Loon* [1997] and *Hurrell et al.* [2003] which indicate that while no preferable time scale of NAO variability is detectable, the NAO exhibit considerable variability at quasi-biennial periods and in the decadal band. More importantly, the studies show that variability in the decadal band was enhanced over the 20th century and has become especially pronounced in the second half of it. However, despite the good agreement with our observations from Little Cayman on decadal time scales, evident multidecadal variability in $\delta^{18}O$ still needs to be addressed. In this context earlier studies have observed that wintertime NAO exhibits significant multi-decadal variability [*Hurrell*, 1995; *Chelliah*, 2004; *Goodkin et al.*, 2008; *Woollings et al.*, 2015]. Interestingly, multidecadal variability observed in both SST and $\delta^{18}O$ (Figure 3) agrees very well with multidecadal variability of wintertime NAO (wintertime NAO to: $\delta^{18}O$, $r = 0.74$; SST_{GS}, $r =$

0.73; SST_{LC}, $r = 0.79$; $p < 0.0001$; comparison of low-pass filtered annual data), suggesting a relation to wintertime NAO. Decadal variability also seems to be influenced by wintertime NAO in such a way that when wintertime NAO (not shown) is low during 1920-1970, covariance between NAO and $\delta^{18}O$/SST is significantly increased in the decadal band (Figure 4). Results from observations and models point to distinct patterns of ocean-atmosphere variability on decadal and multidecadal scales of the NAO [*Deser and Blackmon*, 1993; *Delworth and Mann*, 2000; *Sutton and Hodson*, 2003; *Shaffrey and Sutton*, 2006]. On the decadal time scale NAO is dominated by meridional shifts of the jet stream and associated storm track, whereas on the multidecadal time scale variability is dominated by changes in their strength [*Woollings et al.*, 2015]. Recent studies suggest that the two timescales thereby express non-stationary relationships between NAO and regional impacts on temperature [*Pozo-Vazquez et al.*, 2001; *Haylock et al.*, 2007; *Comas-Bru and McDermott*, 2014] and precipitation [*Vicente-Serrano and Lopez-Moreno*, 2008; *Raible et al.*, 2014] and different relationships to SST [*Raible et al.*, 2001; *Walter and Graf*, 2002; *Raible et al.*, 2005; *Alvarez-Garcia et al.*, 2008]. Especially in Europe the multidecadal component of NAO variability has a clear and distinct influence on surface temperatures and precipitation, so that decadal forecasts of this variability could be of practical use [*Woollings et al.*, 2015]. However, model predictability may be hampered by the assumption of stationarity of the NAO signal, which is commonly used in reconstruction methods[*Küttel et al.*, 2010; *Woollings et al.*, 2015]. This problem is compounded by the complexity of the observed low-frequency variability in the Atlantic, which is subject of intense debate [*Enfield and Mayer*, 1997; *Xie and Tanimoto*, 1998; *Dommenget and Latif*, 2000; *Marshall et al.*, 2001; *Huang et al.*, 2004; *Xie and Carton*, 2004].

Our analyses suggest that the coral, due to its position, tracks changes in NAO variability on both the decadal and the multidecadal time scales in the important Loop Current and Gulf Stream regions (Figure 2). Hence, proxy data from this location may contribute new insights into the temporal and spatial nonstationarity of the NAO and can help to specifically investigate its impact on the western Caribbean and the Gulf Stream region. Moreover, these new proxy reconstructions can be compared with model-generated fields of forced (external and internal) and natural variability over the last centuries. Evaluation of model simulations against paleo-data indicate that models are capable of reproducing trends and large-scale patterns of past climate changes but tend to underestimate or lack distinct signatures of regional changes related to NAO and ENSO [*Küttel et al.*, 2010; *Braconnot et al.*, 2012; *Woollings et al.*, 2015]. Here, higher density of proxy data and distribution over larger geographical areas potentially provide more internally consistent and spatially coherent insights into past climatic variability not covered by instrumental data. However, there are regions of the ocean with naturally low density of available proxy archives due to, e.g. a lack of landmass and associated shallow waters housing potential biogenic proxy archives. Our coral $\delta^{18}O$ record is a clear example for the potential of proxy records to fill these gaps by tracking climate variables, such as SST, over larger regions. To obtain missing information it is crucial to localize the proxy record that potentially contains this information. We compare our $\delta^{18}O$ record to other Caribbean $\delta^{18}O$ data from the Venezuelan Archipelago Los Roques [*Hetzinger et al.*, 2008] and from Puerto Rico [*Kilbourne et al.*, 2008] to visualize geographical differences of SST variability representation between records. Figure 5 shows the spatial correlation patterns of those three records. For more clarity only high negative correlations with $r \leq -0.6$ are considered. Data from Los Roques show a pronounced correlation between coral $\delta^{18}O$ and large-scale SST variability in the northern tropical Atlantic (NTA), the Caribbean Current as well as the Canary Current region, representing the northeastern to southwestern portion of the North Atlantic subtropical gyre. Hence, while our observations and results from earlier studies [*Hetzinger et al.*, 2006b; *Hetzinger et al.*, 2008] indicate that the south-eastern Caribbean record is sensitive to changes in SST and seawater $\delta^{18}O$ in waters upstream from Los Roques (entering the Caribbean from the southeast) our central Caribbean isotope record seems to track SST-changes mainly in waters downstream from the sampling site (leaving the Caribbean in northerly direction). Interestingly, the Puerto Rico record shows highest correlations mainly in two separate regions remote from the location, i.e. the eastern sector of the Equatorial Counter Current and a region including the Azores and Portugal Current and the northern branch of the Canary Current. There is much overlap between the correlation fields of the Puerto Rico and Los Roques records. Despite the overlap additional information is still obtained, specifically in the north, because spatial correlations of the Puerto Rico record extend further into the western central part of the North Atlantic gyre. Our analysis shows that the total acquired spatial coverage of high correspondence between $\delta^{18}O$ and SST variability is large, including principal elements of the North Atlantic subtropical gyre, even though it is based only on three records from three different Caribbean sites. The spatial distribution of correlations of these records clearly demonstrates the potential of proxy data to provide information on SST variability for regions where no instrumental measurements or proxy archives are available and to reconstruct the climate system in periods prior to the instrumental record. A focused application of proxy data from such areas, which also have been identified as "areas of uncertainty" in model based projections by the *IPCC* [2013], has the potential to greatly reduce that uncertainty.

Summary and Conclusions

Here we describe and interpret a 125-year record of coral $\delta^{18}O$ and Sr/Ca variations in the Central Caribbean Sea (Little Cayman, Cayman Islands), representing the longest continuous seasonal resolution record from a Diploria strigosa coral to date.

Both geochemical proxies show a decreasing long-term trend. The calculated warming from $\delta^{18}O$ is within the range of globally averaged surface warming estimates of the *IPCC* [2013] while Sr/Ca indicate a much stronger regional warming in comparison to large-scale grid-SST data. In conjunction with earlier studies [*Kilbourne et al.*, 2008; *Hetzinger et al.*, 2010; *von Reumont et al.*, 2016] our results suggest that Sr/Ca is a better indicator of local changes in temperature, while $\delta^{18}O$ seems to be a better indicator of large-scale/regional scale SST changes and that grid-SSTs not sufficiently represent local SST variability within the reef system.

Seawater $\delta^{18}O$ variations ($\Delta\delta^{18}O_{sw\text{-}center}$) at Little Cayman are successfully captured by the coral proxy record by removing the Sr/Ca derived temperature component from coral $\delta^{18}O$. High inverse correlation with the AMO indicates that when temperature increases precipitation increases and vice versa. After the mid-1970s however, the $\Delta\delta^{18}O_{sw\text{-}center}$ signal decouples from the AMO signal and shifts to a steadily increasing regime, i.e. precipitation decreases while temperature increases. An overall linear trend towards higher $\Delta\delta^{18}O_{sw\text{-}center}$ also indicates a drying trend over the past century. Through its environmental implications a continued drying and increase in temperature could have important socioeconomic consequences in the Cayman Islands and in the whole region.

The $\delta^{18}O$ and Sr/Ca time series show different potential in tracking SST variability on large spatial scales. While Sr/Ca exhibit strong relations with SST restricted to the local level, $\delta^{18}O$ shows high correlation with SST in the Gulf Stream region east of Cape Hatteras and the Loop Current region. Therefore Little Cayman potentially is a sensitive location for the detection of past regional scale SST variability within the Gulf Stream System. More specifically, our $\delta^{18}O$ data tracks changes in NAO variability on both the decadal and the multidecadal time scales in that region. The data may contribute to a basic understanding of the temporal and spatial nonstationarity of NAO and can help to investigate the impact of NAO on the western Caribbean and the Gulf Stream region.

The combined evaluation of our coral $\delta^{18}O$ record and two other records from different Caribbean sites reveals a large total spatial coverage of high correspondence between coral $\delta^{18}O$ and SST variability, comprising principal elements of the North Atlantic subtropical gyre. This result is a clear demonstration of the potential of proxy data to provide information on SST variability for regions where no instrumental measurements or proxy archives are available as well as to reconstruct the climate system in periods prior to the instrumental record. Thereby our new Central Caribbean proxy reconstructions help to increase the density and distribution of proxy data over larger geographical areas, which is important for gaining more internally consistent and spatially coherent insights into past climatic variability not covered by instrumental data.

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Table 1. Linear regression equations between coral $\delta^{18}O$ (Sr/Ca ratios) and $HadISST_{aug}$ data set[a] for the 1887-2011 time period.

Data Set	*Resolution*	*Regression equation*	*r*	r^2	*p*	*σ*
$\delta^{18}O$	monthly	$\delta^{18}O$ = -0.082(0.003) x SST - 1.915(0.093)	-0.54	0.29	<0.0001	0.172
	extreme values	$\delta^{18}O$ = -0.082(0.006) x SST - 1.901(0.17)	-0.65	0.42	<0.0001	0.171
	annual	$\delta^{18}O$ = -0.292(0.039) x SST + 3.973(1.081)	-0.56	0.32	<0.0001	0.117
Sr/Ca	monthly	Sr/Ca = -0.021(0.001) x SST + 9.546(0.023)	-0.56	0.31	<0.0001	0.043
	extreme values	Sr/Ca = -0.027(0.001) x SST + 9.703(0.041)	-0.76	0.58	<0.0001	0.041
	annual	Sr/Ca = -0.069(0.012) x SST + 10.875(0.331)	-0.46	0.22	<0.0001	0.036

[a]Equations are computed using ordinary least squares (OLS) regression with zero-lag, 95% confidence limits for slope and intercept are given. Results from a test between the OLS technique and orthogonal regression did not significantly differ. [b]The residual standard errors are given as σ.

Table 2. Basic statistics of the calibrated δ^{18}O (Sr/Ca) and augmented HadISST data sets for the seasonal cycle and mean annual values[a].

		Seasonal cycle				Mean annual values			
Data Set	*Period*	*Summer*	*Winter*	*Average*	*Range*	*Max*	*Min*	*Range*	σ
$HadISST_{aug}$	1887-2011	29.59	26.11	27.93	3.48	28.50	27.17	1.33	0.27
δ^{18}O	1887-2011	29.42	26.08	27.80	3.34	29.28	27.01	2.27	0.48
Sr/Ca	1887-2011	30.76	26.39	28.56	4.37	29.16	26.55	2.62	0.58

[a]In °C; σ is standard deviation of annual mean values

Table 3. Trend analysis of SST and coral proxy time series (Sr/Ca and $\delta^{18}O$) for the time interval 1887–2011 for three different locations. Trends were computed based on proxy temperature relationships determined in the reference studies and linearly extrapolated where necessary for the overall trend. Original length of records: LC3: 1887-2011, Gua1: 1896-1998, TR: 1751-2004.

		Overall Trend (°C)			
Location	*Coral Core / Data Set*	*Sr/Ca-SST*	*$\delta^{18}O$-SST*	*Gridded SST*	*Reference*
Cayman Islands	LC3	*1.60*	1.06	0.62[a]	*this study*
Guadeloupe	Gua1	*1.63*	0.62	0.64[b]	*Hetzinger et al., 2010*
Puerto Rico	Turrumote Reef	*1.24*	1.63	0.60[c]	*Kilbourne et al., 2008*

		Warming per Decade (°C)			
Location	*Coral Core / Data Set*	*Sr/Ca-SST*	*$\delta^{18}O$-SST*	*Gridded SST*	*Reference*
Cayman Islands	LC3	*0.13*	0.08	0.05[a]	*this study*
Guadeloupe	Gua1	*0.13*	0.04	0.05[b]	*Hetzinger et al., 2010*
Puerto Rico	Turrumote Reef	*0.13*	0.10	0.05[c]	*Kilbourne et al., 2008*

[a]$HadISST_{aug}$ (augmented with CREWS data), [b]ERSST, [c]HadISST

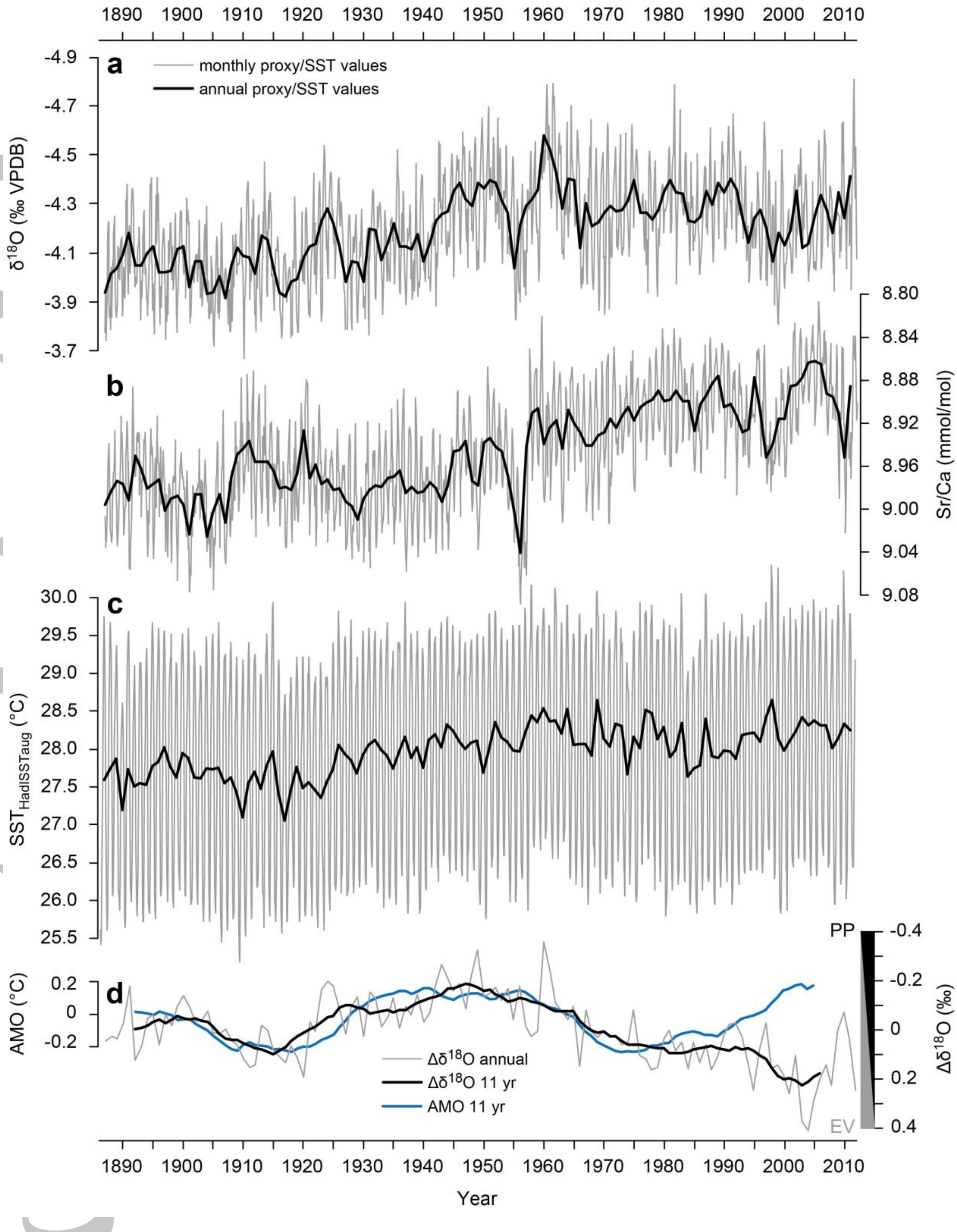

Figure 1. Monthly and annual mean time series (1887-2011) of (a) coral δ^{18}O, and (b) coral Sr/Ca from core LC3 and of (c) the augmented HadISST reanalysis data for the grid box centered on 19.5°N and 79.5°W, including the coral site. (d) Comparison between 11 yr moving average data of coral $\Delta\delta^{18}O_{sw\text{-}center}$ and AMO. Guadeloupe coral $\Delta\delta^{18}O_{sw\text{-}center}$ generated by removing the Sr/Ca-derived temperature component of the coral δ^{18}O signal. The resultant $\Delta\delta^{18}O_{sw\text{-}center}$ is an estimate of seawater δ^{18}O. Note divergence of the $\Delta\delta^{18}O_{sw\text{-}center}$ signal from the AMO from the late 1970s resulting from atmospheric circulation

alterations and changing precipitation patterns in the tropics. PP: Precipitation; EV: Evaporation.

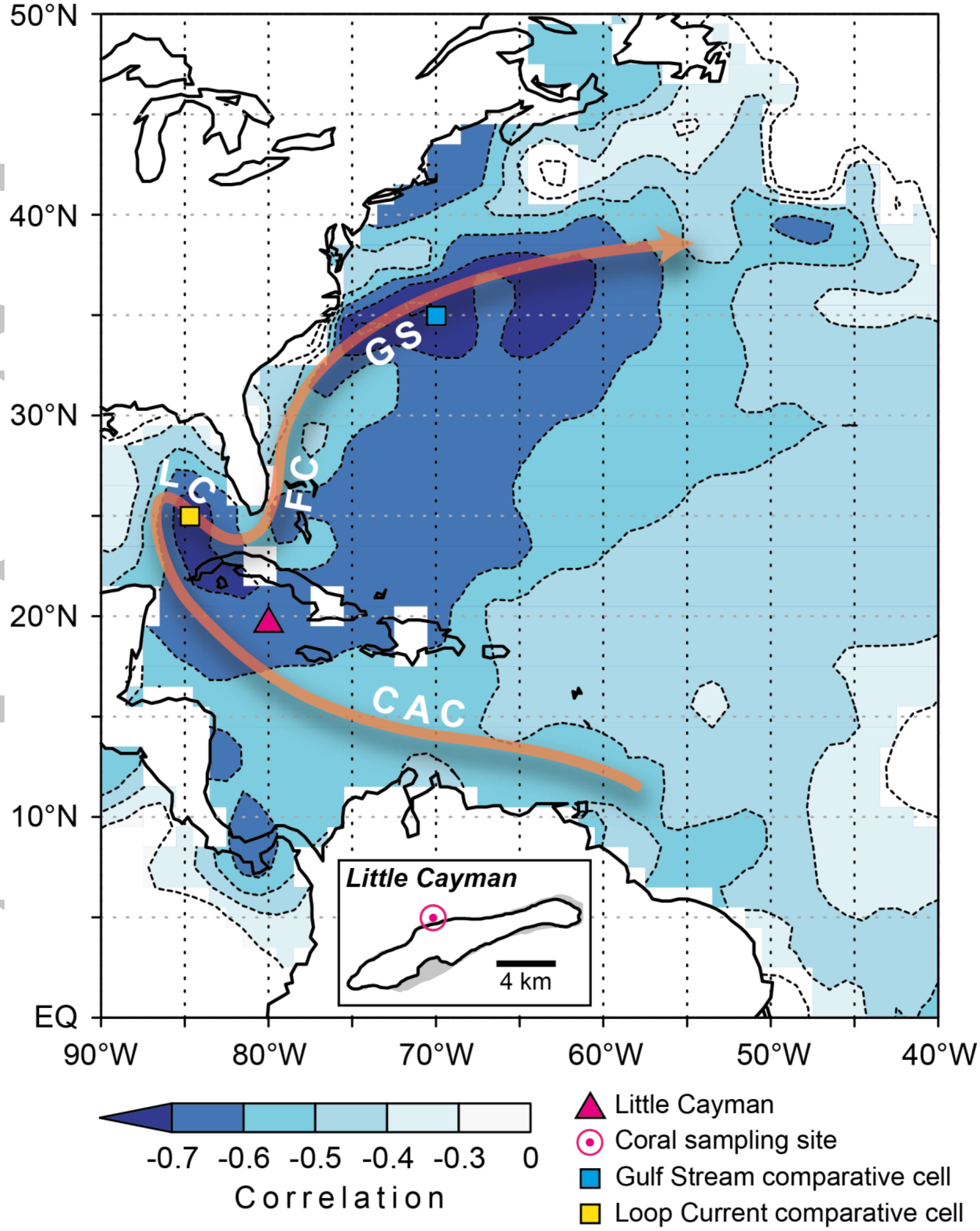

Figure 2. Oceanographic setting of the western North Atlantic and Caribbean region showing major surface currents in the Caribbean and flowing out of it. Surface currents are indicated as orange arrow based on the Mariano Global Surface Velocity Analysis (MGSVA) (http://oceancurrents.rsmas.miami.edu): CAC: Caribbean Current; LC: Loop Current; FC: Florida Current; GS: Gulf Stream. Blue colors represent the spatial distribution of correlations between annual mean coral $\delta^{18}O$ and HadISST data [Rayner et al., 2003]. Data cover the period 1887-2011 and were detrended. Note that correlation of coral $\delta^{18}O$ and HadISST is high and significant at the 1% level especially in the Gulf Stream and Loop

Current region. Spatial distribution of correlations was computed and plotted at http://climexp.knmi.nl/.

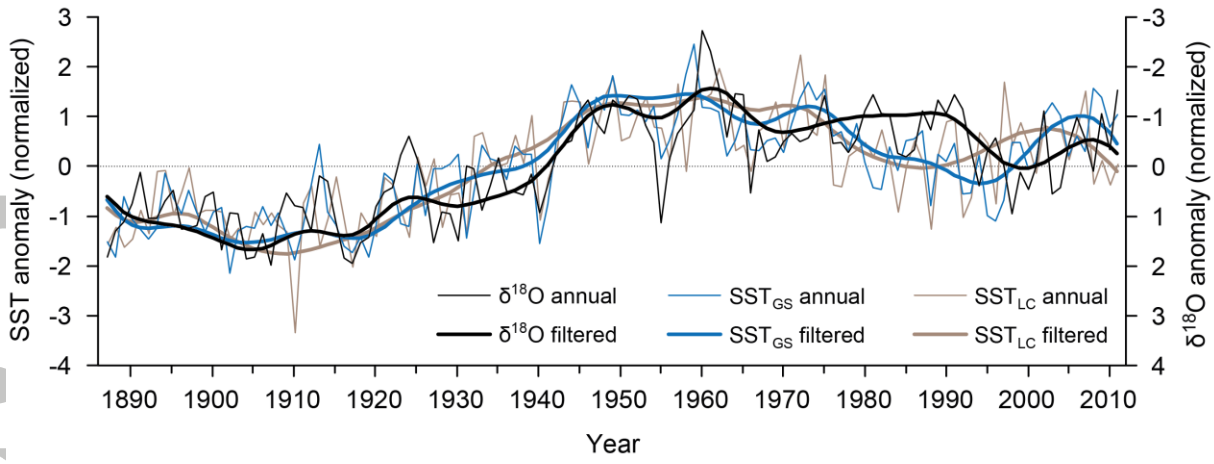

Figure 3. Coral δ^{18}O time series and its relation to sea surface temperature in the Gulf Stream (GS) and Loop Current (LC) comparative grid cells (see Figure 2). Data were normalized to unit variance for comparison by subtracting the mean and dividing by standard deviation. Filtering was done with a 15-year low-pass Gaussian filter.

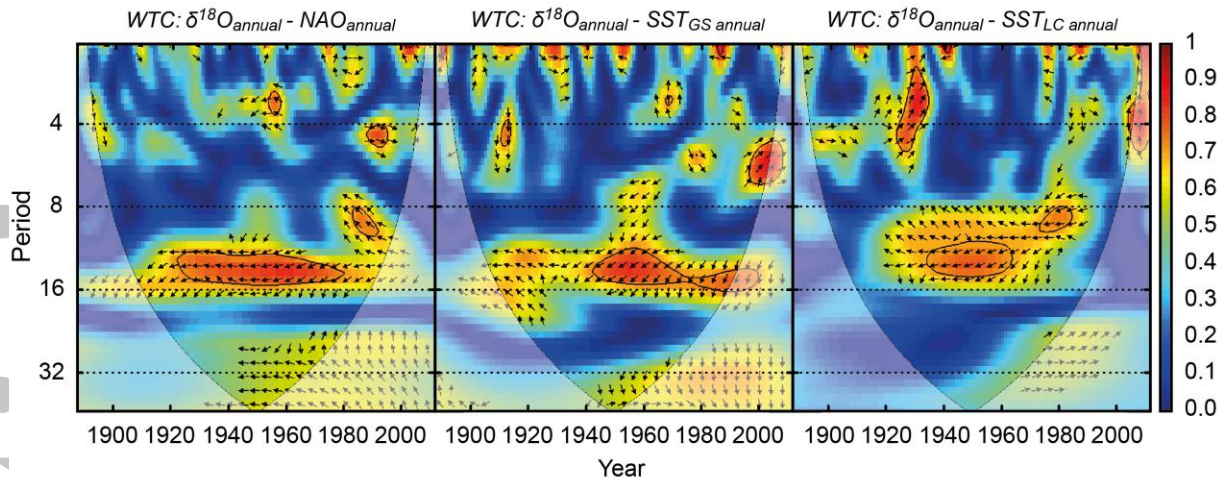

Figure 4. Results from wavelet coherence spectra between annual coral $\delta^{18}O$ and NAO index data as well as between annual coral $\delta^{18}O$ and SST from the Gulf Stream (GS) and the Loop Current (LC) (see Figure 2). The black contour designates the 5% significance level against red noise and the cone of influence where edge effects might distort the picture is shown as a lighter shade. The plots were computed using wavelet coherency software by [*Grinsted et al.*, 2004].

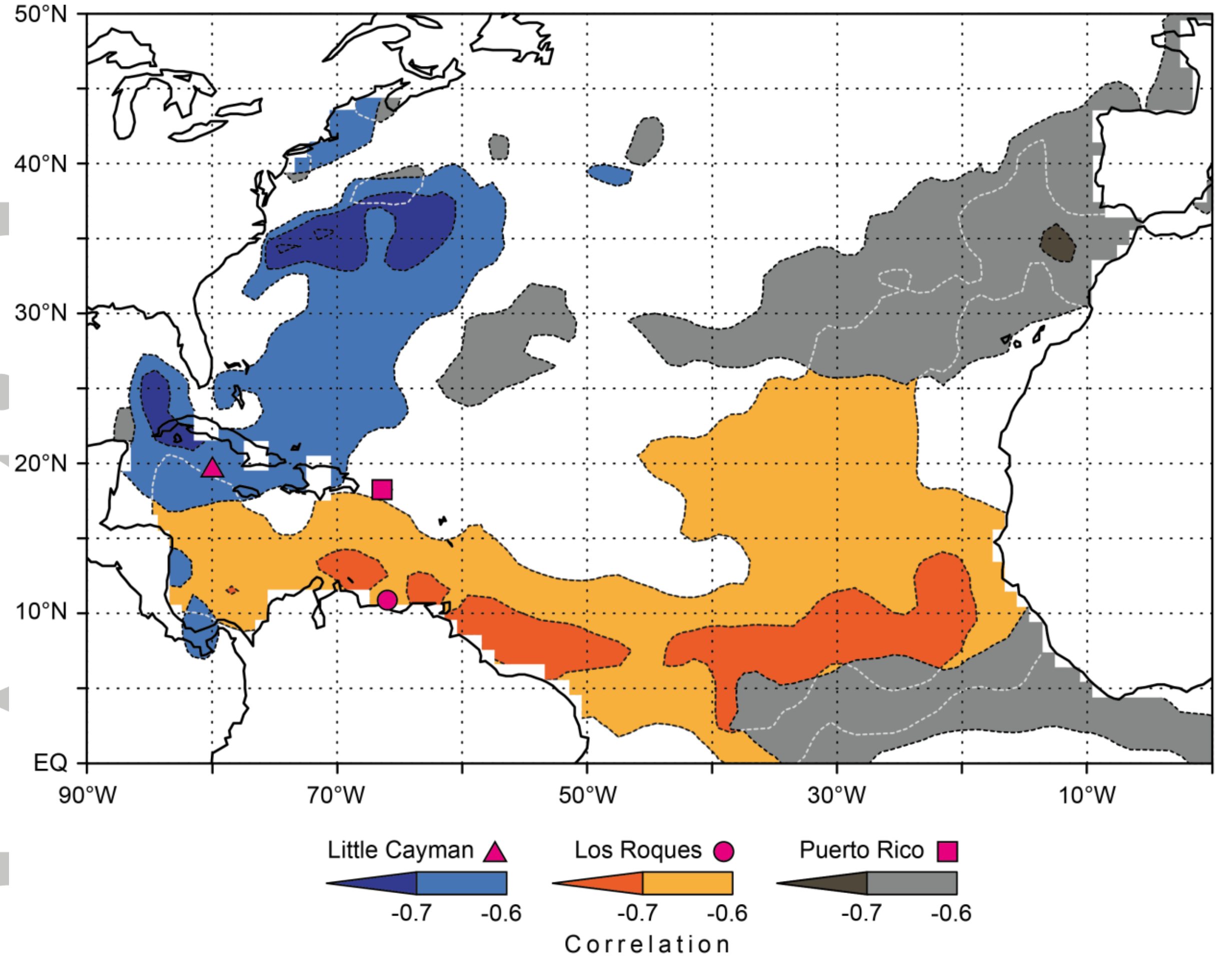

Figure 5. Spatial distribution of correlations between annual mean coral $\delta^{18}O$ and HadISST data [Rayner et al., 2003] for Little Cayman, Los Roques [Hetzinger et al., 2008] and Puerto Rico [Kilbourne et al., 2008]. Data cover the period 1887-2011 (Little Cayman), 1918-2003 (Los Roques) and 1751-2004 (Puerto Rico) and were detrended. For more clarity only high negative correlations with $r \leq -0.6$ are shown. Correlations are significant at the 1% level and were computed and plotted at http://climexp.knmi.nl/. White dashed lines represent the continuing contour line of a correlation field where fields overlap. A three-panel version depicting the correltations to the different corals in full in each panel is provided in Figure S6.