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El Niño–Southern Oscillation–like variability in a late Miocene Caribbean coral

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ABSTRACT

Reconstructions of Pliocene sea-surface temperature (SST) gradients and thermocline depths suggest that the zonal temperature gradient of the tropical Pacific was distinct from the modern. However, the nature of any El Niño–Southern Oscillation (ENSO) variability superimposed on this mean state is difficult to determine. We developed monthly resolved multidecadal stable isotopic time series from an extremely well preserved central Caribbean coral dating to the Miocene-Pliocene transition, prior to closure of the Central American Seaway (CAS). Paleoceanographic modeling suggests that the flow of water associated with El Niño and La Niña events through the CAS allowed Caribbean corals to record the ENSO-related SST anomalies. Spectral analysis of coral oxygen isotope ratios reveals periodicities similar to modern ENSO signatures, suggesting that ENSO-like variability characterized the Miocene-Pliocene transition.

INTRODUCTION

The Pliocene (5.3–2.6 Ma) was characterized by atmospheric carbon dioxide concentrations argued to have been approximately equivalent to modern values and global mean air temperatures ~3 °C higher than today (Haywood et al., 2013). One important but poorly constrained aspect of the Pliocene is the nature of the El Niño–Southern Oscillation (ENSO), a dominant mode of modern interannual global climate variability (Ward et al., 2014). Whereas changes in the mean state of the Pliocene tropical Pacific (e.g., an entrenched El Niño–like pattern) have been proposed based on analyses of foraminifera (Wara et al., 2005; Scroxton et al., 2011), identifying sea-surface temperature (SST) variability associated with ENSO events in these proxies is not straightforward.

Colonial corals can provide stable isotopic records of ocean chemistry and SSTs at the submonthly resolution necessary to reconstruct past ENSO activity (Cobb et al., 2013), but their aragonite skeleton is highly susceptible to secondary alteration that masks or destroys primary paleoenvironmental signals. As a result, only a small number of studies have identified pre-Quaternary corals of sufficient preservation to be useful as paleoceanographic records (e.g., Roulier and Quinn, 1995). One example involves two extremely well preserved Pliocene corals from the western Pacific that revealed oxygen isotopic variability similar to modern ENSO (Watanabe et al., 2011). However, no similar Pliocene coral records have been developed from the eastern Pacific. Corals were abundant in the Caribbean during the Miocene and into the early Pliocene, however, and while the final closure age for the Central American Seaway (CAS) remains the subject of debate (Molnar, 2008; Montes et al., 2015), many studies support a seaway sufficiently open to allow significant exchange of surface waters between the Pacific and Caribbean basins at that time (Keigwin, 1982; Haug et al., 2001; Fig. 1). We take advantage of this oceanographic gateway to test the nature of ENSO at the Miocene-Pliocene transition through construction of two multidecadal monthly resolved isotopic time series from an extremely well preserved central Caribbean coral from the late Miocene, and use the results of a fully coupled climate model to investigate the extent of an oceanic ENSO-Caribbean connection.

PREVIOUS RESEARCH AND ANALYTICAL METHODS

A coral head of the extinct species *Goniopora hilli* was collected from the Miocene Gurabo Formation in the central Dominican Republic and is estimated to have grown above 20–30 m depth (Goreau, 1959). Burial occurred in one of the many fine-grained sedimentary deposits

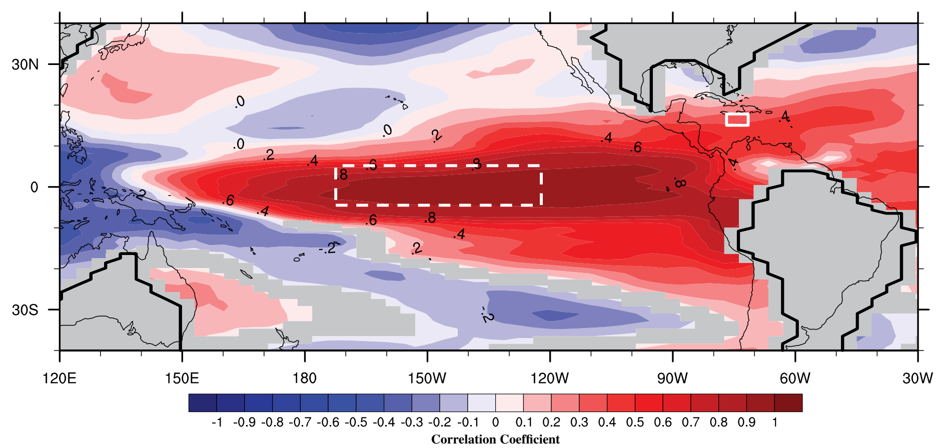

Figure 1. Cross-correlation map (color shading) between the modeled early Miocene sea-surface temperature (SST) and NINO3 (lat 5°N–5°S, long 150°–90°W) index (SST averaged over the dashed rectangle). Model simulations performed using the Community Climate System Model (CCSM1.4; http://www.cesm.ucar.edu/models/ccsm1.4/) with early Miocene boundary conditions, including atmospheric pCO2 of 710 ppm (Von Der Heydt and Dijkstra, 2011). Solid rectangle denotes Miocene location of the Dominican Republic that, in the model context, is in the positive correlation region. Bold lines denote early Miocene continental boundaries; light lines are modern boundaries. Central American Seaway geometry shown is wider and deeper than existed in late Miocene.

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of the Gurabo Formation that restricted interaction with groundwater, thereby allowing an extraordinary degree of preservation (Saunders et al., 1986). This particular *G. hilli* sample previously underwent extensive screening for signs of diagenetic alteration using a variety of petrographic, stable isotopic, radioisotopic, scanning electron microscopy (SEM), and X-ray diffraction (XRD) techniques and has been demonstrated to be in nearly pristine condition; the coral maintains well-defined calcification centers, septal ornamentation, growth laminae, and primary porosity, as well as no detectable calcite (Denniston et al., 2008a). U-Pb techniques were used to date the sample to 5.52 ± 0.15 (2 standard deviations) Ma, placing it at the Miocene-Pliocene transition (Denniston et al., 2008a).

The coral skeleton was cut into slabs parallel to corallite growth axes using a water-cooled trim saw, and the chips were impregnated with epoxy and mounted to glass slides as ~1-mm-thick sections that were sampled for stable isotopic ratios. We have extended a previously published isotopic time series (corallite-1; Denniston et al., 2008b) and developed a new time series from a separate portion of the same coral head (corallite-2). In both cases, individual corallites were sampled in 150-mm-wide traverses corresponding to submonthly resolution. The resulting powders were processed using off-line methods, and $\delta^{18}O$ and $\delta^{13}C$ values were determined using a Finnigan MAT Deltaplus XL mass spectrometer in continuous flow mode with a gas bench and CombiPal autosampler at Iowa State University (Ames, USA; see the GSA Data Repository[1]). Portions of corallite-1 had been analyzed at the University of Michigan (Ann Arbor, USA; Denniston et al., 2008b). The carbon isotope ratios agree well between laboratories, but $\delta^{18}O$ values are offset by ~0.6‰, an effect we attribute to roasting in vacuo at the University of Michigan (Gaffey et al., 1991). However, the ranges and trends of data from both laboratories are similar, and thus adjusting for this offset does not appear to have affected our results, especially the spectral properties. Isotopic values are presented in parts per mil (‰) relative to the Vienna Peedee belemnite carbonate standard (VPDB). Precision was determined by regular analysis of standards interspersed among the samples and is better than 0.1‰ for both carbon and oxygen.

In order to assess periodicities in the coral time series, oxygen isotope data were interpolated into regular 12 points per year, and then analyzed using a 2–7 yr bandpass filter (https://github.com/CommonClimate/common-climate/blob/master/wavelet_filter.m) from the Wavelet toolbox (Torrence and Compo, 1998) in MatLab. As a complement to this approach, the data were decomposed into linear trends, seasonal components, and residuals using Breaks For Additive Season and Trend (BFAST; Verbesselt et al., 2010) (Fig. DR1 and Methods section in the Data Repository). These residuals were analyzed for their spectral characteristics using both wavelet (Torrence and Compo, 1998) and multitaper methods (MTM; Thomson, 1982) (Fig. DR2). Although the coral was previously screened for diagenesis, to reduce the likelihood that the analysis was corrupted by isotopic values associated with undetected areas of alteration we conducted spectral analyses of the original data as well as data filtered to remove anomalous points prior to analysis with BFAST (Fig. DR3).

In order to understand the oceanic connection between the Pacific ENSO system and the Caribbean Sea, we make use of model simulations using the Community Climate System Model (CCSM1.4) of the National Center for Atmospheric Research (Boulder, Colorado, USA). The CCSM is a fully coupled global ocean–atmosphere–land–sea ice general circulation model, simulating the evolution of climate under external forcing conditions without the use of flux corrections (Blackmon et al., 2001). The model faithfully reproduces modern ENSO variability and teleconnections (Blackmon et al., 2001; Otto-Bliesner and Brady, 2001) (Fig. DR4). Here we apply a long simulation under idealized early Miocene boundary conditions (including a wide open CAS) and a modern control simulation, as described in Galeotti et al. (2010) and Von Der Heydt and Dijkstra (2011). The width and depth of the CAS in the model is substantially greater than would have occurred in the late Miocene, but the exact geometry of the CAS is not well known, and thus this configuration is useful to examine only broad flow characteristics associated with ENSO and the CAS (Fig. 1). In the corresponding present-day simulation with a closed CAS, there exists a weak but significant correlation between the Niño Region 3 (lat 5°N–5°S, long 150°–90°W) SST and the Caribbean SST (Fig. DR5). In Galeotti et al. (2010), the Miocene simulation was shown to establish an ENSO teleconnection to the Mediterranean region, where high-resolution records suggested enhanced ENSO-related precipitation variability in the Miocene.

Variations in the oxygen isotopic composition of coral aragonite are attributable either to changes in shallow marine temperature or source water isotopic composition (related to salinity) (Roulier and Quinn, 1995). Possible sources of oscillatory climate signals operating at interannual time scales in the Caribbean Sea include ENSO and the North Atlantic Oscillation (NAO), both of which undergo complex interactions (Giannini et al., 2001). ENSO is more prominent even though its impacts on the Caribbean are weak relative to the eastern Pacific, as its influences are transmitted largely through precipitation and wind speed (Giannini et al., 2001). The NAO is predominantly a high-latitude phenomenon, but affects Caribbean rainfall (Jury et al., 2007). Our model simulations of both modern and Miocene time suggest an active NAO with weak to negligible correlation with the Caribbean SST and precipitation (Fig. DR6), and thus NAO is considered to have had little impact. As the Caribbean ENSO signal may have been enhanced in the Miocene due to an extra oceanic teleconnection between the Caribbean Sea and the Pacific, we consider ENSO as the most likely source of oxygen isotopic variability in this coral.

INTERANNUAL SST VARIABILITY IN THE MIOCENE CARIBBEAN SEA

Clearly defined seasonal cycles in both carbon and oxygen isotopic ratios reveal 27 and 29 yr of growth in corallite-1 and corallite-2, respectively (Fig. 2), with numerous positive and negative isotopic anomalies relative to the average seasonal cycle (Fig. DR7). Spectral analysis of the oxygen isotopic data using both bandpass and BFAST methods identifies statistically significant activity across the ENSO band (Fig. 3). Using bandpass filtered data, wavelet analysis reveals periodicities located squarely in the 2–7 yr ENSO band for both corallites. MTM analysis yields periodicities of 2–12.5 yr and 2–8 yr for corallite-1 and corallite-2, respectively (although in corallite-2, the power density drops below the 95% confidence interval from 2.7 to 3.0 yr). Similar periodicities exist between these corallite time series and modern periodicities in the Niño Region 3 of the tropical Pacific as well as in the modern Caribbean (Fig. DR8). Using the BFAST method, periodicities are apparent in both wavelet and MTM at >95% confidence, and identify the predominant spectral power at 2–5 yr, similar to, albeit somewhat more frequent than, the modern ENSO band (although unfiltered data yield a 2–7 yr power spectrum, identical to modern ENSO periodicities). Similar characteristics are also apparent in the raw data (Fig. DR9).

Because ENSO events occur during boreal winter, temperature-dependent fractionation effects (-0.2‰/°C) (Grossman and Ku, 1986) on oxygen isotopic ratios during aragonite crystallization would have recorded El Niño–induced anomalous warming of Caribbean surface waters as lower than expected winter $\delta^{18}O$ values, and La Niña–induced cooling would have produced higher than expected winter values. This response would likely have been enhanced by changes in regional precipitation accompanying ENSO. Rainfall anomalies are observed in the tropical eastern Pacific during El Niño and La Niña events (Wallace et al., 1998), and given that rainfall has lower $\delta^{18}O$ values than seawater, changes in Caribbean sea surface salinities

[1]GSA Data Repository item 2017208, data file of oxygen and carbon isotopes versus distance in corallite-1 and corallite-2, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

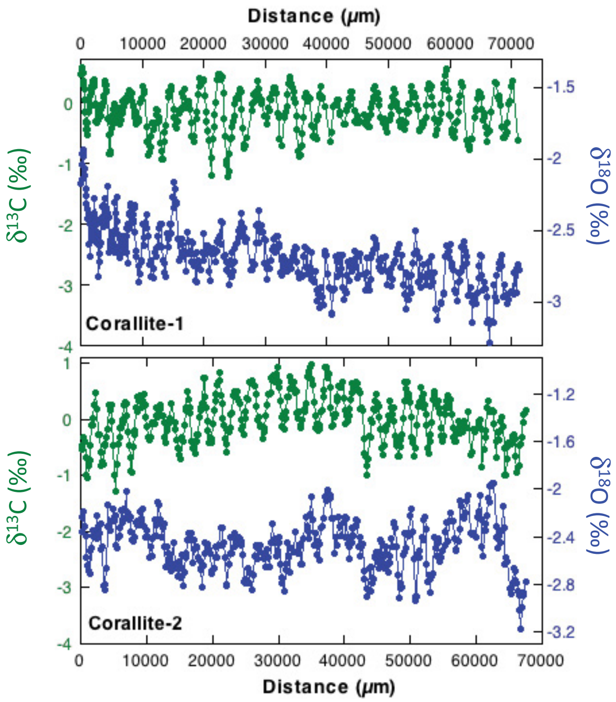

Figure 2. Filtered *Goniopora hilli* stable isotopic time series. Data suspected of alteration were removed using a standardized filtering method in which the linear approximation for each point was calculated as the linear interpolation of surrounding two points.

during ENSO events would have compounded the effects of SST anomalies on coral $\delta^{18}O$ values. Specifically, enhanced rainfall during El Niño events would have lowered sea surface oxygen isotope ratios, amplifying the response of coral aragonite to warmer water temperatures.

The temporal evolution of CAS geometry is an important but poorly understood component of paleoceanographic models, and dates for final closure are the subject of debate (Molnar, 2008; Montes et al., 2015). Montes et al. (2015) interpreted the presence of Isthmus of Panama–derived zircons in middle Miocene sedimentary sequences from northern South America as indicating a fluvial connection between the two sites (and thus closure of that portion of the CAS) by ca. 10 Ma, although they also noted that continued exchange between the Caribbean and Pacific waters could have occurred to the north and west. However, similar Caribbean and Pacific foraminifera oxygen isotope values support the flow of Pacific surface waters into the Caribbean through the Miocene (Keigwin, 1982), with shoaling to an average depth of ~200 m by ca. 6 Ma concurrent with the presence of scattered islands that allowed for the migration of terrestrial species between the Americas (Molnar, 2008). The geology of the CAS becomes difficult to precisely constrain after ca. 6 Ma, but foraminifera stable isotope values from the Pacific and Caribbean were not distinct until ca. 2.7 Ma, indicating that uplift of Central America did not fully sever the connection between the Pacific and Caribbean until that time (Keigwin, 1982).

In order to test the role of an open CAS on establishing an oceanic connection between the Pacific ENSO system and the Caribbean, we compare the Miocene CCSM simulation (with 5-km-deep and 1500-km-wide open CAS, a configuration that is more open than would have occurred during the latest Miocene) with modern-day control simulation (closed CAS). The model suggests that the upper 100 m of water

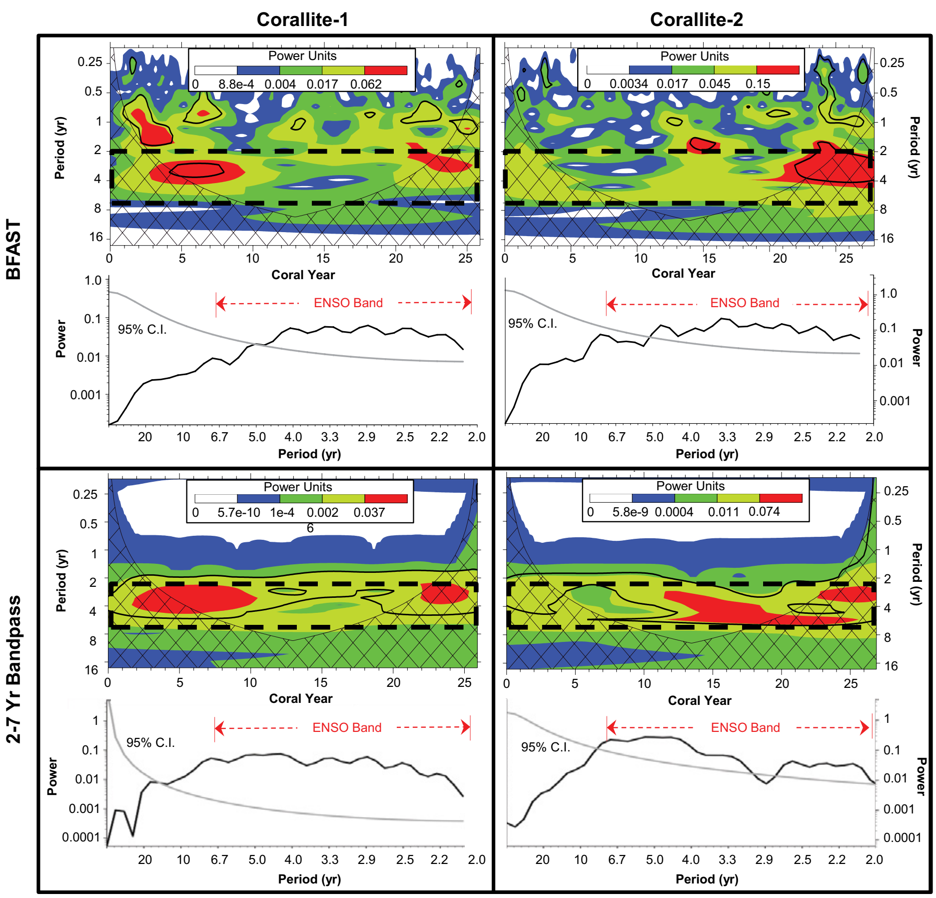

Figure 3. Spectral analyses of *Goniopora hilli* oxygen isotopic time series treated with breaks for additive season and trend (BFAST) and bandpass filtering. BFAST treatment (top panel) shows wavelet (top) and multitaper methods (MTM) (bottom) analyses of corallite-1 and corallite-2. Wavelet analyses are based on Torrence and Compo (1998); Morlet wavelet, parameter = 6, start scale = 2, scale of width = 0.25, powers of two = 11. MTM analyses performed using kSpectra version 3.4.3 (www.spectraworks.com; resolution = 2, number of tapers = 3). Bandpass filtered (2–7 yr window; bottom panel) results are shown using wavelets (top) and MTM (bottom) of corallite-1 and corallite-2. For wavelets, contour levels are chosen so that 75%, 50%, 25%, and 5% of wavelet power is above each level, respectively. The cross-hachured region is the cone of influence, where zero padding has reduced the variance. Black contour is 95% confidence level (C.I.—confidence interval). For MTM, gray line denotes 95% confidence level. El Niño–Southern Oscillation (ENSO) band reflects modern 2–7 yr recurrence interval. Both wavelet and MTM techniques used a red-noise (autoregressive lag1) background spectrum to determine significant periodicities.

in the CAS flowed west to east from the Pacific to the Caribbean, reaching the location of the Dominican Republic (Fig. DR10). As a result, SST in the central Caribbean and Niño Region 3 of the tropical Pacific were strongly correlated, although the correlation is much weaker in the modern simulation where the teleconnection exists only via the atmosphere (Fig. DR5). Moreover, with an open CAS, the extension of the North Equatorial Counter Current into the Caribbean Sea is stronger during El Niño events, and weaker during La Niña events, further enhancing the correlation between Caribbean SST and the Niño regions index.

The *G. hilli* oxygen isotopic time series contain significant power predominantly across the ENSO band, largely similar to a Pliocene coral from the western Pacific (Watanabe et al., 2011; Fig. DR11). This finding is in contrast to climate modeling with an open CAS that suggests that east Pacific ENSO-related SST anomalies were able to penetrate into the Caribbean, expanding the geographic extent over which the Bjerknes feedback operates, slowing the recharge-discharge cycle of the ENSO system, and thereby increasing the ENSO recurrence interval (Von Der Heydt and Dijkstra, 2011). Alternatively, some evidence suggests that the Pliocene El Niño may have concentrated in the central Pacific, rather than the canonical form of many modern events (such as the 1982–1983 El Niño) in which warming is concentrated in the eastern portion of the basin (Molnar and Cane, 2007).

CONCLUSIONS

Oxygen isotopic ratios from an extremely well preserved late Miocene coral from the central Caribbean contain power spectra similar to modern ENSO variability observed in the tropical Pacific and consistent with ENSO reconstructions from a western Pacific Pliocene coral. Model simulations suggest a stronger than modern oceanic connection between ENSO and the Caribbean Sea with an open CAS. Although rare, corals such as this that preserve their original aragonite skeleton offer important insights into past paleoceanographic behavior and should form the basis for future studies into pre-Quaternary climate phenomena. Future analysis using an isotope-enabled climate model will provide an important test of these claims.

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