Multisite Record of Climate Change from Indian Ocean Corals

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Abstract Coral records from coastal East Africa spanning 2° to 7°S (Kiwayu, Malindi, Watamu, Mombasa, Kisite, and Mafia) demonstrate that isotopic tracers preserved within coral aragonite accurately record intraseasonal to interannual changes in sea surface temperature. The strong seasonal signal observed at all six sites most likely reflects sea surface temperature variability forced by ocean circulation and reversals in wind direction associated with the Indo-African Monsoon. Strong southwesterly winds during the Southwest Monsoon initiate evaporative cooling and mixing, resulting in a sea surface temperature minimum in the late boreal summer. Coral $\delta^{18}0$ values are higher during this period. Reproducibility in the coral $\delta^{18}0$ signal between sites indicates that an individual coral isotope records from the coast of East Africa can be used to reconstruct regional climatic conditions. We present the first <u>multisite</u> analysis of sea surface temperature variability along the East African coast as recorded in the isotopic composition of reef corals.

Introduction

Climate in the Indian Ocean is forced by complex interactions between ocean currents, sea surface temperature (SST), and atmospheric circulation at intra- and interbasinal spatial scales. As a result, climate change in the Indian Ocean, and particularly the Afro-Asian Monsoon region, is not easily predicted. The implications of improved predictability are significant for those countries affected by the monsoon. The failure or delay of the monsoon can have life-threatening consequences for inhabitants of India, East Africa and Indonesia. The global economic system is now so intimately linked that the impact of a failed monsoon is felt worldwide. Consequently, financial and agricultural systems as well as human health may benefit from improved understanding and predictability of Indian Ocean climate.

The Afro-Asian monsoons develop in response to the large thermal gradients between the Asian continent and the Indian Ocean. During the northern hemisphere winter, a high-pressure cell develops over the Asian land mass and contributes to the creation of the northeast monsoon. The pressure gradient between the land and ocean forces winds from the northeast to southwest and drives surface ocean circulation anti-clockwise. In response to northeasterly winds, surface waters are driven to the west or southwest in the equatorial Indian Ocean (Rao and Griffiths 1998).

During the northern hemisphere summer, a low-pressure cell develops over the Asian landmass forming the southwest monsoon. From June to September strong southwesterly flow in the lower troposphere brings moisture to the Indian subcontinent and Himalayas. Reversals of the Somali Current are also linked to the Afro-Asian monsoons. Responding to prevailing winds, increased upwelling and strengthening of the Somali Current occur along the northern coasts of Somalia and Oman from June to September (Luther 1999).

Long records of SST variability from western Indian Ocean corals provide valuable insights into the intraseasonal and interannual dynamics of the Afro-Asian Monsoon. Isotopic tracers within coral aragonite can accurately record seasonal and annual changes in environmental parameters such as precipitation, river input, salinity, and sea surface temperature (Dunbar et al. 1996; Fairbanks et al. 1997; Evans et al. 1999; McCulloch 1999). Coral growth rates of millimeters to centimeters per year permit us to resolve subannual environmental changes. Here we present the first multisite analysis of coral $\delta^{18}0$ variability along the East African coast. A single site record from Kenya suggests significant decadal variability that is strongly associated with tropical Pacific SST's (Cole et al. 2000). In this paper we assess the between-site variability in order to evaluate the reliability of single-site coral climate records in East Africa.

Background

Most coral paleotemperature records are developed from the analysis and interpretation of the oxygen isotopic composition ($\delta^{18}O$) of coral aragonite ($CaCO_3$). Coral $\delta^{18}O$ varies as a function of temperature and the $^{18}O/^{16}O$ ratio of seawater, often related to salinity. Numerous records of past variability in SST and salinity have been reconstructed using coral $\delta^{18}O$ (e.g., Charles et al. 1997; McCulloch 1999; Swart et al. 1999; Cole et al. 2000). According to the pioneering work of Epstein et al. (1953), the $\delta^{18}0$ of biogenic calcium carbonate decreases by approximately 0.22 ‰ for every 1°C rise in water temperature. Calibration efforts demonstrate that coral $\delta^{18}0$ values parallel monthly instrumental SST's (e.g., Shen et al. 1992; Wellington et al. 1996). The sensitivity of coral $\delta^{18}0$ to changes in precipitation and SST has allowed scientists to significantly extend our understanding

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of ENSO beyond what can be obtained from the instrumental record alone (Cole et al. 1993; Wellington et al. 1995; Dunbar et al. 1996; Evans et al. 1999; Le Bec et al. 2000; Linsley et al. 2000; Urban et al. 2000).

The application and regional significance of coral paleoclimate records depend on their reliability and consistency. Concerns regarding the reproducibility of the $\delta^{18}O$ signal include metabolic and growth rate effects. For instance, subannual variation in skeletal calcification and extension rates are possible sources of aliasing of temperature signals, and slow growth rates are linked to signal attenuation (e.g., Lough and Barnes 1990; Allison et al. 1996, deVilliers et al. 1995, McConnaughey 1989). Therefore, in concert with developing multi-decadal $\delta^{18}O$ records from individual coral colonies, it is also important to assess between and within-colony $\delta^{18}O$ reproducibility in order to distinguish large-scale climate changes from those that may be due to either local effects or biological artifacts.

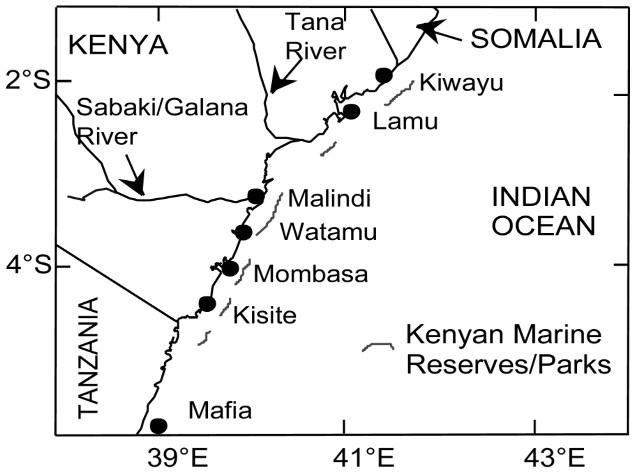

Fig. 1 Short coral cores were collected by drilling massive colonies of *Porites lutea* off the coasts of Kenya and Tanzania at the 6 sites shown.

Methods

Cores collected from massive hermatypic corals (*Porites lutea*) off the coasts of Kenya and Tanzania were sampled along a transect from 2°S to 7°S to assess the seasonal and spatial variability in the coral $\delta^{18}O$ signal (Fig. 1). R. Dunbar and G. Shen recovered coral cores in 1997 from the following sites in Kenya: Kiwayu (2°2'S, 41°15'E), Malindi (3°14'S, 40°8'E), Watamu (3°23'S, 39°52'E), Mombasa (3°59'S, 39°45'E), and Kisite (4°43.079'S, 39°22.838'E). J. Cole recovered an additional core used for this study from Mafia, Tanzania (7°S, 40°E) in 1998. The reef sites all lie under 1 to 4 m of seawater. The Galana River, located approximately 15 km to the north of Malindi, seasonally influences that site during the fall runoff season. While the river water appears to contribute to the trace element chemistry of the corals (Dunbar et al., in prep.), the $\delta^{18}O$ of local river water is approximately 0 $^{o}/oo$, suggesting that the river has a negligible affect on the seawater $\delta^{18}O$.

X-radiography of the cores reveals pronounced annual variations in skeletal density and growth rates ranging from 6 to 15 mm/yr. A transect was mapped along a prominent growth axis of each core and sampled continuously from the top of the coral slab to approximately 80-mm depth. Subannual samples for isotopic analysis were collected using a low speed drill to extract aragonite powder every 1-mm. The sampling procedure yielded an average of 13 samples per year, except at Kisite where the growth rate appears to be approximately 6 mm/yr. Corals from Kiwayu, Malindi, Watamu, Mombasa, and Kisite were analyzed at Stanford. The Mafia coral was analyzed at the University of Colorado/INSTAAR's stable isotope lab. In the Stanford procedure, aliquots of coralline aragonite weighing 55 to 95 µg were acidified with 2 to 3 drops of H_3PO_4 at 70°C and analyzed using an automated individual carbonate-reaction (Kiel) device coupled to a Finnigan MAT 252 mass spectrometer. At the INSTAAR lab, samples of ~0.5mg were reacted in a common acid bath at 90°C and analyzed on a Micromass Optima isotope ratio mass spectrometer with an automated Isocarb preparation system. Approximately 15% of the samples were replicated, yielding an average standard deviation of less than 0.05 $^{o}/oo$ for $\delta^{18}O$. Unknowns were calibrated against a known standard (NBS-19) and in-house standards at Stanford and Colorado (SLS-1 and Luxor, respectively). All results are reported relative to PDB.

Monthly Global sea-Ice and SST (GISST 3.2) temperature data sets (Rayner et al., 1996), at 1° x 1° resolution, were used to develop seasonal chronologies and to calibrate the oxygen isotope time series. Appropriate GISST records were chosen according to their proximity to a specific coral site. The following coordinates for the GISST 3.2 data and their respective coral site are listed here: 2.5°S, 41.5°E (Kiwayu), 3.5°S, 40.5°E (Malindi, Watamu and Mombasa), 4.5°S, 39.5°E (Kisite) and 7.5°S, 39.5°E (Mafia).

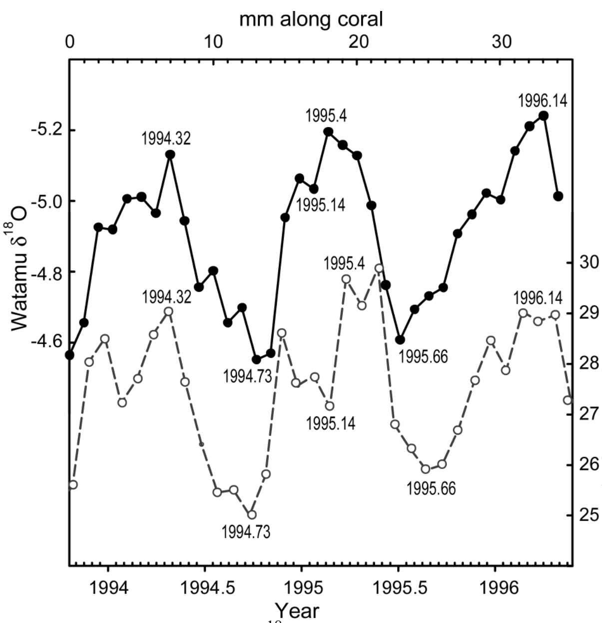

Fig. 2 Oxygen isotope ($\delta^{18}O$) profile versus depth in a coral core from Watamu for the most recent 2 years (upper – registered as a function of depth in mm) compared with GISST 3.2 ocean temperature data (lower – registered as a function of month/year). The dates on each curve are calendar age "pick points" for aligning the coral depth data with the monthly SST data in order to construct an optimized sub-annual age model.

Instrumental records along the transect from 2° to 7°S indicate that the maximum (minimum) temperature off the coasts of Kenya and northern Tanzania occurs in March/April

(July/August). Accordingly, the minimum and maximum coral $\delta^{18}0$ values were assigned the corresponding GISST calendar date (Fig. 2). A minimum of 3 and maximum of 5 dates per year were used from the GISST data to assign calendar ages to the $\delta^{18}0$ time series. These pick-points or tie lines include annual minimum and maximum values, as discussed above, as well as a cooling episodes during mid-boreal winter (typically in January), as well as transitions periods between the monsoons expressed as a change in slope of the isotope profile (Fig. 2). This method is designed to probe how good the calibration might be if the age model is optimized so as to minimize age model errors. The method maximizes the coherency between coral isotope data and the instrumental record of SST, but only in the time domain. For longer paleoclimate reconstructions such subannual tuning is not possible. We perform it here simply to assess the maximum possible coherency between multiple isotope records and a commonly used instrumental data set. In longer records that extend prior to the advent of reliable instrumental data (~1950 A.D. at this location) the positions of the annual low and high density bands may be used to assign ages at a near-seasonal resolution, but only if seasonal timing of the formation of these bands is relatively constant. In this case we did observe strong and consistent correspondence between changes in skeletal density and assigned calendar month (based on the GISST matching protocol), so this approach does appear justified, with the caveat that our evaluation data set only spans the period 1990-1996. The minimum $\delta^{18}0$ values during the boreal spring months lie within the high-density bands. During this period when SST is high, calcification rate increases relative to extension rate, producing a high-density skeletal band.

After assigning ages to 3 to 5 pick points each year, samples in between these points were linear interpolated to make an initial age model with unequal time steps. Next, each series was resampled at a constant monthly resolution for direct comparison with each other as well as with the GISST instrumental data set. Correlation analysis of these data sets is very much biased towards recognition and description of the annual cycle. Often, in coral paleoclimate work, we are most interested in interannual variability. In this case, in order to evaluate the coherency of interannual climate anomalies between the six sites, we deseasoned the $\delta^{18}0$ time series by subtracting site-specific monthly average values (calculated at each site from the entire series) from each monthly-registered isotopic value.

Results

Oxygen isotope results from the six corals are displayed in Figure 3 for the period 1990-1996. Time-series analysis indicates that the annual signal dominates coral $\delta^{18}0$ variability at all six sites, accounting for approximately 80% of the variance. During some years a second cooling episode is observed in January, associated with the onset of the boreal winter monsoon. Correlation analysis, as expressed in a Pearson Product Correlation matrix (Table 1), illustrates the temperature dependence of the $\delta^{18}0$ signal at all six sites, with coral $\delta^{18}0$/GISST r values ranging from –0.86 to –0.60. The correlation between the individual $\delta^{18}0$ records from the different sites varies between 0.84 and 0.50, with an average correlation of 0.68 (Table 1). The correlation coefficients for the deseasonalized $\delta^{18}0$ values are not as strong and removing the seasonal signal diminishes the temperature dependence (Table 2). However, there was only one significant interannual SST anomalies during 1990-1996 and the amplitude of the deasonalized $\delta^{18}0$ series is generally low (series' standard deviations are 0.08 to 0.14 ‰) and approaches the analytical error of ~0.05 to 0.08 ‰. Nevertheless, the correlations in Table 2 provide some information about the ability of corals to record subtle interannual variability relative to a large seasonal cycle. Linear least-squares regression equations describe the calibration of coral $\delta^{18}0$ to GISST monthly temperature (Table 3). The results shown in Table 3 are generally in agreement with those established for water-carbonate exchange reactions (i.e., Epstein et al. 1953) and the range of slope values reported for *Porites* (e.g., Weber and Woodhead 1972; Wellington et al. 1996; McConnaughey 1989; Gagan et al. 1994; Linsley et al. 1999).

Table 1[a] Pearson Product Correlation values for coral isotope times series and GISST

Site	GISST	Kiwayu	Malindi	Watamu	Mombasa	Kisite	Mafia	6 site composite
GISST	1	-0.75	-0.78	-0.86	-0.74	-0.60	-0.82	-0.87
Kiwayu[1]		1	0.67	0.70	0.70	0.54	0.58	0.83
Malindi[2]			1	0.79	0.84	0.72	0.71	0.94
Watamu[2]				1	0.73	0.59	0.76	0.89
Mombasa[2]					1	0.74	0.56	0.89
Kisite[3]						1	0.50	0.80
Mafia[4]							1	0.79

[a] Pearson Product Correlation values (α=0.05) were calculated between the six coral sites (Kiwayu, Mombasa, Watamu, Malindi, Kisite and Mafia) using the original $\delta^{18}0$ values, as well as a 6-coral composite isotope record, and the GISST 3.2 temperature time series for the period 1990-1996. The following list represents the GISST 3.2 coordinates used in the correlation matrix: [1]2.5°S, 41.5°E, [2]3.5°S, 40.5°E, [3]4.5°S, 39.5°E and [4]7.5°S, 39.5°E.

Table 2[b] Pearson Product Correlation values for deseasonalized coral isotope times series and GISST

Site	GISST	Kiwayu	Malindi	Watamu	Mombasa	Kisite	Mafia
GISST	1	-0.12	-0.14	-0.18	-0.13	-0.12	-0.09
Kiwayu[1]		1	0.29	0.43	0.34	0.26	0.07
Malindi[2]			1	0.40	0.51	0.49	0.25
Watamu[2]				1	0.30	0.22	0.19
Mombasa[2]					1	0.54	-0.18
Kisite[3]						1	0.04
Mafia[4]							1

[b]Pearson Product Correlation values (α=0.05) for deseasonalized $\delta^{18}O$ values for each of the six coral sites (Kiwayu, Mombasa, Watamu, Malindi, Kisite and Mafia) and the GISST 3.2 temperature time series for the period 1990-1996. Deseasonalizing was accomplished by subtracting the average isotopic value for each calendar month (determined using all 6 months – e.g. each of 6 successive January values) from each monthly value. The following list represents the GISST 3.2 coordinates used in the correlation matrix: [1]2.5°S, 41.5°E, [2]3.5°S, 40.5°E, [3]4.5°S, 39.5°E and [4]7.5°S, 39.5°E.

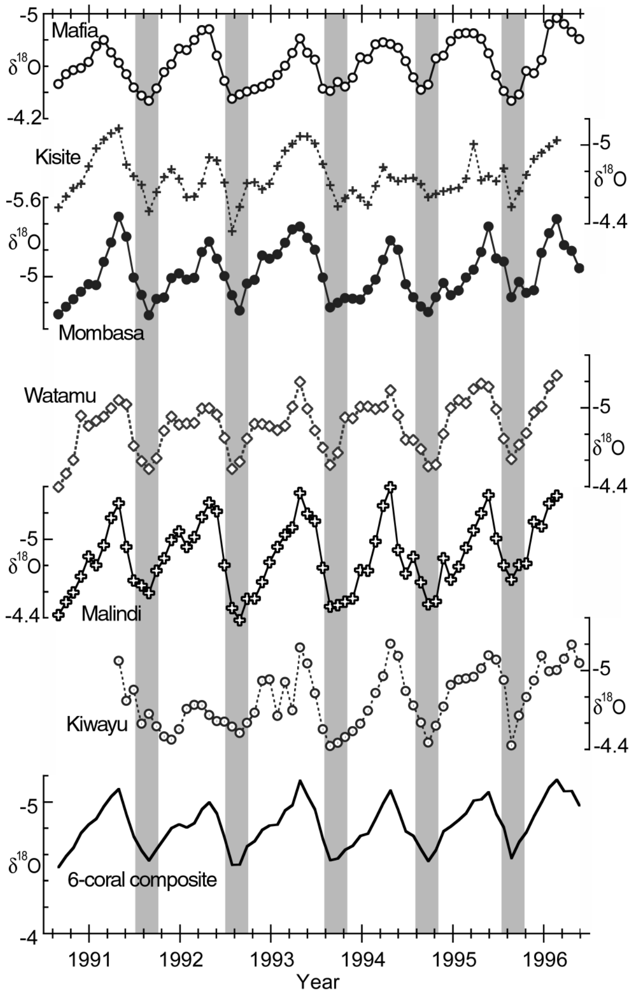

Fig. 3 Oxygen isotope ($\delta^{18}O$) time series for the six coral sites (top to bottom: Mafia, Kisite, Mombasa, Watamu, Malindi, Kiwayu) and a 6-coral composite produced by averaging monthly values from all 6 sites. These series demonstrate common variance in $\delta^{18}O$ values between 1990 and 1996.Vertical gray bars simply highlight the seasonality.

Discussion

Seasonal interpretation

The strong seasonal signal observed at all six sites off the coast of East Africa (Kiwayu, Malindi, Watamu, Mombasa, Kisite and Mafia) reflects SST variability forced by ocean circulation and winds. For example, evaporative cooling and vertical mixing due to strong southwesterly winds during the SW Monsoon results in lower SST in the late summer, when the coral $\delta^{18}0$ values are the highest. Instrumental SST records indicate a seasonal change of approximately 4°C. Assuming a mixed layer depth of 30 m and reported average wind velocities, evaporative cooling alone could account for more than half of this observed change (up to 2.4°). In contrast, during the monsoon transition (April) when the winds are the lightest, SST's increase and these conditions are reflected in more negative coral $\delta^{18}0$ values. The seasonal temperature dependence is revealed in the calibration slopes and correlation coefficients. Averaging all six $\delta^{18}0$ time-series shows that the instrumental SST record and a 6-site composite coral oxygen isotope record share 76% of their variance (Fig. 4).

During some years a seasonal doublet in the mid to late boreal winter is observed in the instrumental record and is also present in the coral $\delta^{18}0$ time-series (Fig. 3). A short cooler period during the thermal maximum typically involves a temperature decrease of less than a degree, equivalent to a change of less than 0.35-0.16 ‰, depending on the coral site. Given the nature of our physical sampling of these corals and the analytical error (on the order of 0.05 to 0.08 ‰), it is not surprising that this seasonal doublet is not always evident in the isotope profiles.

Multisite reproducibility

Coral-based oxygen isotope time series recovered from 2°S to 7°S along the coast of East Africa suggest that variability in SST and ocean circulation associated with the reversing monsoons dominates the coastal ocean region. Reproducibility of the coral $\delta^{18}0$ signal between sites is evident in the coupling observed in the time series from the six records (Fig. 3 and Tables 1 and 2). As shown in Figure 3 and highlighted by the gray vertical bars, the coherency observed between the time series suggests that growth rate and/or disequilibrium effects do not significantly influence the similarity of the seasonal signals. The correlations between the six sites decrease when the annual cycle is removed, suggesting that for this limited period between 1990-1996, the correlation is driven mostly by the seasonal cycle. We expect that these coral's utility for recording climate anomalies is more easily demonstrated when working with longer time series wherein climate anomalies, rather than the annual cycle, account for a greater percentage of variance in $\delta^{18}0$. However, as shown in Figure 3, deviations from the seasonal cycle are synchronous during certain years between the six sites. Furthermore, on average, the three months with the highest $\delta^{18}0$ values exhibit a strong correlation to

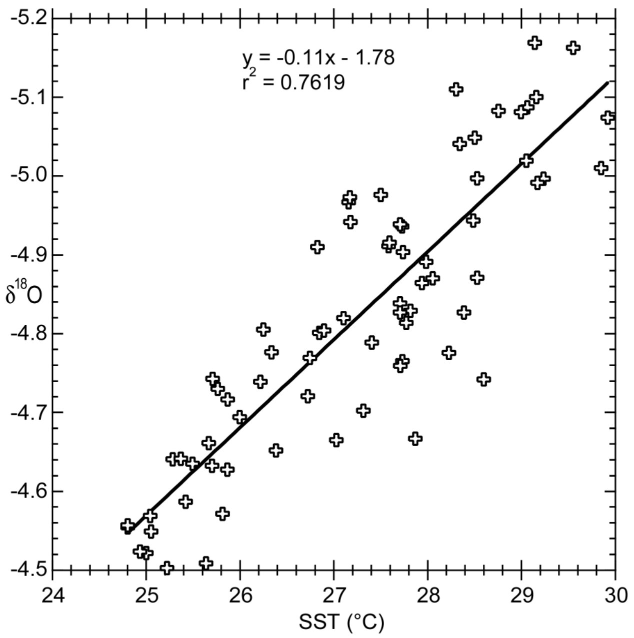

Fig. 4 Crossplot and linear regression results from the 6-coral composite $\delta^{18}O$ values and the average instrumental monthly sea-surface temperature data sets (GISST 3.2; 1x1 degree grids). There is strong coherency (r = -0.87) between the instrumental and proxy sea-surface temperature record off the coast of Kenya and northern Tanzania.

the three coldest months with r = -0.70. Calculating an annual correlation, rather than a seasonal correlation, reveals in even stronger relationship, r = -0.90. We recognize that interpreting these relationships should be limited due to the brevity of the time series, nonetheless, this work is promising and illustrates the strong temperature dependence and coherency of the coral $\delta^{18}0$ signal on both intraseasonal and interannual time scales along the coast of East Africa.

Table 3 Linear regression equations for monthly oxygen isotope results versus GISST 3.2 temperature

Site	Equation	n	slope
Kiwayu	SST=7.35-4.12($\delta^{18}0$ coral)	62	-0.24
Malindi	SST=7.93-3.95 ($\delta^{18}0$ coral)	67	-0.25
Watamu	SST=-1.76-5.95 ($\delta^{18}0$ coral)	67	-0.17
Mombasa	SST=1.73-5.07($\delta^{18}0$ coral)	72	-0.20
Kisite	SST=0.52-5.62($\delta^{18}0$ coral)	67	-0.18
Mafia	SST=-8.44-7.75 ($\delta^{18}0$ coral)	72	-0.13
6-site composite*	SST=-5.67-6.83 ($\delta^{18}0$ coral)	67	-0.15

*The six-site composite represents an average of the six different coral time series versus the average of the four different GISST 3.2 time series (see text for coordinates of the GISST data). The Watamu, Mombasa and Malindi sites are represented share the same GISST data.

Conclusions

Isotope-based environmental reconstructions from East African corals provide a robust archive of paleoclimate information. Reversing oceanic circulation and wind direction during the monsoons, and the ensuing change in SST contribute to thermal maxima and minima that are clearly expressed in coral $\delta^{18}0$ composition. This calibration study illustrates the dominant role that SST plays in controlling intraseasonal $\delta^{18}0$ variability. The $\delta^{18}0$ time-series are coherent between six different coral sites ranging from 2°S to 7°S. Variance due to changes in vital or disequilibrium effects is minimal and does not significantly affect the strong seasonal imprint on the $\delta^{18}0$ signal. These findings are encouraging and lend credibility to climate reconstructions derived from single cores collected from the East African coast.

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