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El Niño during the last interglacial period recorded by a fossil coral from Indonesia

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Abstract. Measurements of oxygen isotopes and elemental ratios in a fossil coral that grew 124,000 years ago in North Sulawesi, Indonesia, reflect interannual variability in precipitation and sea surface temperature (SST) due to the El Niño/Southern Oscillation (ENSO). This indicates that ENSO was robust during the last interglacial period, a time when global climate was slightly warmer than the present. The pattern of ENSO frequency behavior in the past is similar to variability in modern instrumental records, but distinct from the most recent period since the mid-1970s, supporting the hypothesis that ENSO behavior in recent decades is anomalous with respect to natural variability.

Introduction

The El Niño/Southern Oscillation (ENSO) is the largest source of interannual climate variability, with impacts on precipitation patterns and temperature centered in the tropical Pacific, and also important at a global scale (Cane, 1986). Several studies have shown that El Niño events have become more severe and have occurred more frequently in recent decades (e.g., Trenberth and Hoar, 1996, 1997). This change in behavior comes at a time of rapidly increasing global temperature (Houghton et al., 1996), prompting the hypothesis that ENSO may be responding to human-induced greenhouse forcing (Trenberth and Hoar, 1996), although the issue is still debated (e.g., Rajagopolan et al., 1997). The possibility that ENSO is intensifying emphasizes the need for understanding the long-term behavior of this important climate system. ENSO records from the pre-industrial era are needed to help establish the natural baseline of variability, as well as identify possible links between ENSO behavior and mean climate (e.g., mean tropical Pacific sea surface temperature (SST)).

During El Niño, the Western Pacific Warm Pool and Indonesian Low migrate eastward toward the central Pacific, attenuating the normal rainy season in Indonesia and causing drought. This is seen in instrumental precipitation data from Manado in North Sulawesi, Indonesia, that show a high degree of correlation with Darwin sea level pressure (SLP) ($r = -.84$) (Moore, 1995). An oxygen isotope ($\delta^{18}O$) time series from a modern coral on Bunaken Is., near Manado (Moore, 1995), correlates well with Manado precipitation and ENSO indices, including Darwin SLP, Tahiti-Darwin Southern Oscillation Index (SOI), and NINO3 eastern equatorial Pacific SST anomaly (SSTA) (Kaplan et al., 1998). The coral $\delta^{18}O$ time series records mild as well as severe El Niño and La Niña events and has a power spectrum nearly identical to the ENSO indices (Moore, 1995). Here we present a geochemical record of past ENSO variability from a fossil coral that grew on Bunaken Is. during the last interglacial period, ~124 thousand years ago (kyr BP). Geochemical evidence demonstrates the absence of diagenetic alteration in the fossil coral. Interannual variability in the fossil record is consistent with the ENSO signature in modern corals from the same site, and frequency analysis of the new record is used to investigate ENSO variability in the past.

Methods

For this study, an individual *Porites* coral head ~2 m in height was found in growth position in a raised coral terrace on Bunaken Is. (Figure 1). The fossil coral was dated by U-Th disequilibrium, using the methods of Edwards et al. (1986).

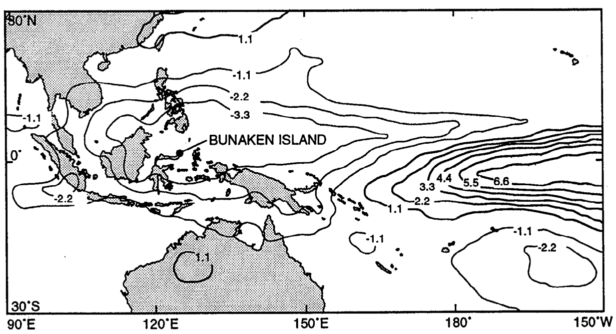

Figure 1. Location of Bunaken Island, off the coast of Manado, North Sulawesi, Indonesia. Contour lines show precipitation anomalies (in mm/day) from the long-term average resulting from the 1982-1983 El Niño. Thin lines are negative anomalies representing drought conditions, and heavy lines are positive anomalies. Anomalies show the characteristic migration of the Western Pacific Warm Pool and precipitation maximum eastward toward the dateline during severe El Niños. Located within the maximum anomaly, central Indonesia is ideally located as a sensitive recorder of mild, as well as severe, El Niño and La Niña events. Data are from the NOAA Climate Diagnostic Center.

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Isotope ratios were measured on a Finnigan MAT 262 thermal ionization mass spectrometer. Two overlapping coral cores were sampled to provide a continuous high-resolution record of paleoclimate. For paired stable isotopic and elemental ratio analyses, ~2 mg of powder was drilled at 1mm intervals along the growth axis. Carbon and oxygen isotope ratios were measured on a Micromass Optima isotope ratio mass spectrometer with automated carbonate device. External precision for samples of powdered carbonate standard are 0.03‰ for $\delta^{13}C$ and 0.06‰ for $\delta^{18}O$ (1σ). Sr/Ca ratios were measured on a JY-46 inductively coupled plasma atomic emission spectrophotometer (Schrag, 1999). Long-term precision of Sr/Ca measurements is better than 0.2% (1σ). The $\delta^{18}O$ and Sr/Ca time series from the two separate cores overlapped at years 35-39 and were spliced together to create a 65-year long record (Figure 2).

Results and Discussion

Geochemical Records

Three samples taken from different places in the fossil coral colony provide ages of 126.7 ± 1.9 ka, 121.9 ± 2.0 ka, and 124.7 ± 3.4 kyr BP (Table 1), indicating the coral grew during the last interglacial period, Marine Isotope Stage (MIS) 5e. The ^{238}U content averages 2.62 ppm, similar to the range of values reported for fossil corals of the same age (e.g., Edwards et al., 1986). Initial $\delta^{234}U$ for the coral averages ~161‰, slightly higher than the value for modern seawater (~144‰)(Chen et al., 1986). Elevated initial $\delta^{234}U$ is commonly found in fossil corals from the last interglacial period (e.g., Edwards et al., 1986), and may indicate either that the coral has experienced open-system conditions (diagenesis) or that seawater $\delta^{234}U$ was higher in the past. If seawater $\delta^{234}U$ was higher in the past or if diagenesis added ^{234}U soon after coral death, then the U-Th ages are accurate as reported. However, if ^{234}U was added late in the coral's exposure history, then the ages reported here could be underestimated by as much as 2500 years, still placing the coral within the high sea level stand of the last interglacial period.

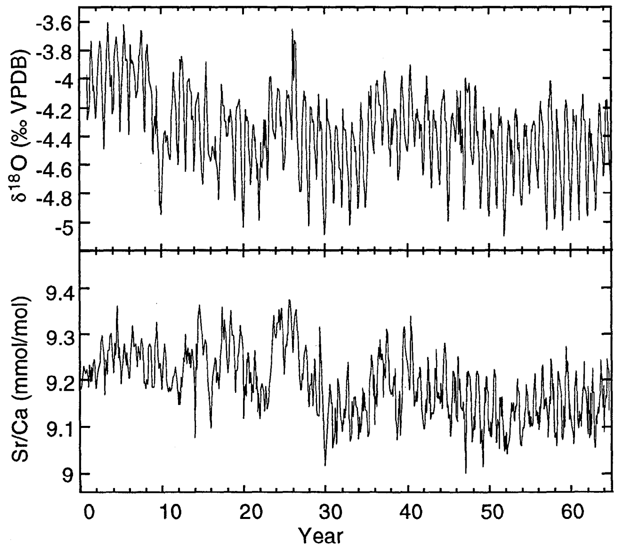

Figure 2. $\delta^{18}O$ and Sr/Ca records from the fossil coral. Average sampling resolution is 12 samples per year. Vertical scales for $\delta^{18}O$ and Sr/Ca are normalized to show the same temperature sensitivity.

$\delta^{18}O$ in corals is determined by SST and $\delta^{18}O$ of seawater during calcification. On monthly to interannual timescales, $\delta^{18}O$ of seawater around Bunaken Is. matches that of the open western Pacific, and is correlated with salinity and the seasonal cycle of rainfall (Moore et al., 1997). The warm SSTs and high rainfall of the wet monsoon combine to cause modern coral $\delta^{18}O$ values to decrease, whereas the colder dry season produces high $\delta^{18}O$ values. The cooler SSTs and drought conditions caused by El Niño create large positive $\delta^{18}O$ anomalies apparent as attenuated or missing minima in the annual $\delta^{18}O$ cycle in both modern (Moore, 1995) and fossil Bunaken Is. corals (Figure 2). With an extension rate of 1.2 ± 0.1 cm/yr, the sampling resolution (~1 month) of the fossil records adequately resolves the seasonal cycle. The mean $\delta^{18}O$ value for the fossil coral is -4.3‰, ~1‰ higher than the average for modern Bunaken Is. corals (-5.2‰) (Moore, 1995). The seasonal cycle in the fossil $\delta^{18}O$ record is higher amplitude and more regular than in modern corals from Bunaken Is.

To identify the SST signal within the $\delta^{18}O$ record, we also measured Sr/Ca ratios, a proxy for SST independent from salinity (Beck et al., 1992). Sr/Ca ratios in the fossil coral average 9.19 mmol/mol, slightly lower than modern Bunaken corals (9.27 mmol/mol), and with a slightly larger amplitude annual cycle. The difference in mean $\delta^{18}O$ and Sr/Ca values for fossil and modern corals suggests that oceanographic conditions at Bunaken Is. may have been warmer and saltier than today during the last interglacial period. However, variability in slope and intercept values for the different calibration equations, even for the same species within the same geographic region (e.g., Alibert and McCulloch, 1997), as well as potential changes in seawater composition over this time scale (Stoll and Schrag, 1998), require that climatic comparisons using corals from different time periods be made with caution. Nonetheless, this Sr/Ca evidence for increased tropical Pacific SSTs during the last interglacial period agrees with sea-level and ice core evidence for a warmer global climate at this time (Jouzel et al., 1987).

Variability in the fossil coral $\delta^{18}O$ and Sr/Ca records covary strongly at annual (coherence = 0.98) as well as interannual time scales (coherence = 0.7-0.9 for periods from 2-7 years), in agreement with the modern correlation of Bunaken Is. SST and precipitation over monthly to interannual periods. The relative amplitude of the signal in the two records (Figure 2) shows that $\delta^{18}O$ receives ~50% of its seasonal and interannual variability from SST, with the remaining variability due to seasonal changes in salinity as a direct result of monsoon precipitation. We did not subtract the Sr/Ca SST record from $\delta^{18}O$ in order to reconstruct a pure record of precipitation because this amplifies the analytical errors from both records. The higher amplitude of the seasonal cycle of $\delta^{18}O$ in the fossil coral relative to modern, with a smaller comparable change in the amplitude of Sr/Ca, is consistent with an increase in the strength of the SE Asian monsoon. Atmospheric GCM experiments (Prell and Kutzbach, 1987) suggest that the SE Asian monsoon was stronger during MIS 5e due to changes in orbital precession resulting in maximum insolation forcing over the northern hemisphere.

Diagenesis

A concern when interpreting the $\delta^{18}O$ and Sr/Ca time series is that recrystallization of aragonite into calcite in contact with meteoric water may affect Sr/Ca ratios and stable isotopes

Table 1. Results of U-Th analyses of fossil coral.[a]

Sample	^{238}U (ppm)	($^{230}Th/^{238}U$) activity	$\delta^{234}U(0)$[b]	$\delta^{234}U(T)$[c]	Age(kyr BP)
BO-0	2.534 ± .003	.7783 ± .0013	112.7 ± 5.5	161.4 ± 7.0	126.7 ± 1.9
BO-3 I	2.929 ± .002	.7581 ± .0039	112.8 ± 3.7	159.4 ± 4.3	121.9 ± 2.0
BO-3 II	2.397 ± .002	.7735 ± .0087	115.4 ± 3.3	164.4 ± 3.2	124.7 ± 3.4

[a]All errors are 2σ.
[b]$\delta^{234}U(0)$ is the measured $^{234}U/^{238}U$ activity ratio normalized to the equilibrium ratio: $\{[(^{234}U/^{238}U)_{meas}/(^{234}U/^{238}U)_{eq}] - 1\} \times 1000$.
[c]$\delta^{234}U(T)$ is the initial $\delta^{234}U$ at the time of growth.

($\delta^{18}O$ and $\delta^{13}C$) (Allan and Matthews, 1982). In order to quantify the effects of diagenesis on our geochemical records, we measured $\delta^{18}O$, $\delta^{13}C$, Sr/Ca and aragonite/calcite ratios on samples with and without visible signs of diagenetic alteration. Samples used for construction of paleoclimate time series were >99.9% aragonite. With as little as 5-10% calcite, the geochemical indicators drop below the range of the seasonal cycle observed in unaltered material. Sr/Ca shows nearly 2.5 times the sensitivity of $\delta^{18}O$ to the same degree of alteration, and even slight diagenesis in the paleoclimate records would be discernable through its larger impact on Sr/Ca than $\delta^{18}O$. The greater amplitude in seasonal and sub-decadal interannual variability in $\delta^{18}O$ compared to Sr/Ca (Figure 2) is consistent with SST and precipitation changes being the primary cause and incompatible with a diagenetic explanation.

Paleo-ENSO record

The distinct interannual variability in the $\delta^{18}O$ record demonstrates that ENSO was robust during a time in the past of slightly warmer mean climate. These results from the last interglacial contrast with studies from the early Holocene suggesting that ENSO variability was diminished, possibly due to the warmer climate at that time (Sandweiss et al., 1996; Rodbell et al., 1999). We used the Blackman-Tukey and multiple-taper methods to estimate the power spectra for modern and paleo-ENSO records (Blackman and Tukey, 1958; Thomson, 1990). The fossil coral time series were filtered with a 1.8-20 year bandpass filter prior to spectral analysis to eliminate noise from the prominent annual cycle. Power spectra were also calculated for unfiltered time series to ensure that the peak locations and distribution of power in the 2-7 year band were not biased by filtering. The power spectrum for the fossil coral $\delta^{18}O$ record has variance concentrated in the characteristic 2-7 year ENSO band, with large peaks at 2.75, 3.5, and ~6 years. A similar concentration of peaks in the 2-7 year band also occurs in the power spectrum for Sr/Ca, although modern instrumental data show that SST is not as highly correlated to ENSO as precipitation in this region. In order to assess changes in ENSO behavior, we compared power spectra for the fossil coral $\delta^{18}O$ record and the modern eastern equatorial Pacific NINO3 SSTA record (Figure 3). For the modern ENSO record, previous workers have shown that spectral power shifts from lower amplitudes and longer periods (5-7 years) to higher amplitudes and shorter periods (3-5 years) in the 1970s (Kumar et al., 1999), possibly coincident with an abrupt shift in atmospheric and oceanic circulation in 1976 (Trenberth and Hoar, 1996; Guilderson and Schrag, 1998). The change in dominant frequency can be seen clearly in power spectra for the NINO3 record from 1856-1976 and 1960-1998 (Figure 3). We used 1960-1998 to describe the most recent period because the NINO3 record from 1976-1998 provided too short a time series for the adequate resolution of individual spectral peaks. The power spectra for fossil coral $\delta^{18}O$ and the NINO3 record prior to 1976 are strikingly similar, in sharp contrast to the NINO3 power spectrum for the most recent period (Figure 3). Comparing power spectra between the fossil and a modern (1950-1990) coral $\delta^{18}O$ record confirms the recent increase in amplitude of ENSO variability, with the modern coral showing nearly twice the amplitude of the last interglacial in the 2-7 year band. Although it is difficult to evaluate the statistical significance of the changes in ENSO after 1976 (Trenberth and Hoar, 1996, 1997; Rajagopalan et al., 1997), the expanded view of natural

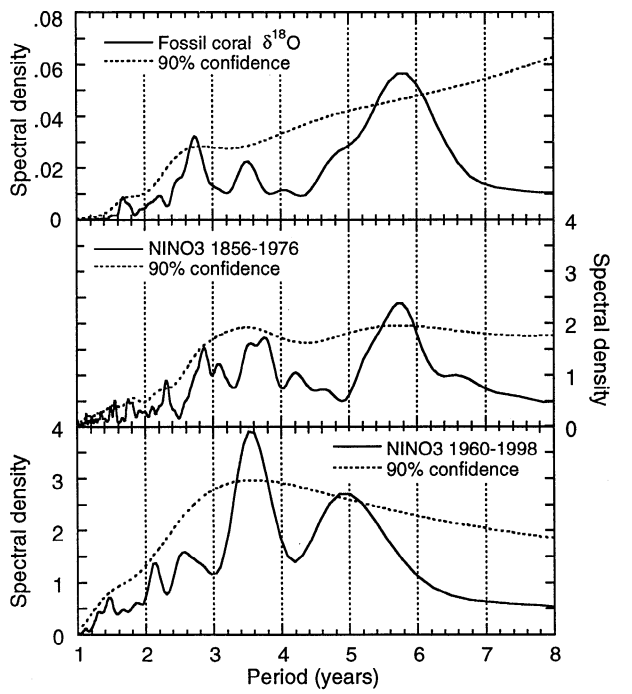

Figure 3. a) Blackman-Tukey power spectrum for fossil coral $\delta^{18}O$. Maximum resolution (solid line) was achieved by lagging the autocorrelation function 50% of the time series; bandwidth = .05 yr^{-1}. Dashed line is 90% upper confidence limit calculated from autocorrelation function lagged 10% of time series; bandwidth = .23 yr^{-1}. b) B-T power spectra for NINO3 SSTA record for the period 1856-1976; bandwidth = .025 yr^{-1} and .125 yr^{-1}. c) B-T power spectra for NINO3 SSTA, 1960-1998; bandwidth = .08 yr^{-1} and .38 yr^{-1}.

variability provided by our fossil coral record suggests that ENSO may be relatively stable during interglacial periods, and that the recent pattern of ENSO is unusual. If the recent changes in ENSO are in fact due to changing climate, then the fact that our record comes from a time of slightly warmer mean climate suggests that the intensification of the higher frequency variability of ENSO may result not from the warmer mean conditions, but from the rate of change in boundary conditions (i.e., warming).

Conclusions

Geochemical records of SST and precipitation were generated from a fossil coral that grew during the last interglacial period (~124 kyr BP). The fossil coral comes from a location in Indonesia that is sensitive to precipitation anomalies associated with ENSO, as demonstrated by previous work on modern corals. Evaluation of potential diagenetic effects indicates that the geochemical records preserve primary environmental variability associated with ENSO. Spectral analysis of the $\delta^{18}O$ record from the fossil coral reveals ENSO variability with frequencies nearly identical to the early instrumental period (1856-1976). Changes in ENSO magnitude and frequency after 1976 appear anomalous with respect to both the earlier instrumental and last interglacial periods, and support the hypothesis that recent ENSO behavior lies outside the range of natural variability.

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