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Evidence for stronger El Niño-Southern Oscillation (ENSO) events in a mid-Holocene massive coral

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Abstract. We present a 47-year-long record of sea surface temperature (SST) derived from Sr/Ca and U/Ca analysis of a massive *Porites* coral which grew at ~ 4150 calendar years before present (B.P.) in Vanuatu (southwest tropical Pacific Ocean). Mean SST is similar in both the modern instrumental record and paleorecord, and both exhibit El Niño-Southern Oscillation (ENSO) frequency SST oscillations. However, several strong decadal-frequency cooling events and a marked modulation of the seasonal SST cycle, with power at both ENSO and decadal frequencies, are observed in the paleorecord, which are unprecedented in the modern record.

1. Introduction

In the last two decades we have witnessed a change in the mode of El Niño-Southern Oscillation (ENSO), with more frequent and stronger El Niño events [*Trenberth and Hoar*, 1996, 1997; *Trenberth and Hurrell*, 1994]. Whether this modulation of ENSO is a result of superimposition of other natural oceanic cycles or is induced by some external factor, such as increasing atmospheric greenhouse gases, is still debated [*Harrison and Larkin*, 1997; *Holbrook and Bindoff*, 1997; *Latif et al.*, 1997; *Guilderson and Schrag*, 1998; *Zhang et al.*, 1998] and is a question of some importance to predictive models of climate change. One way to differentiate among the potential causal agents is to examine ENSO behavior from a time period where increasing greenhouse gasses is not an issue. Since instrumental sea surface temperature (SST) records do not extend that far back in time, we have to rely on proxies to generate long, high-resolution SST data sets. It is now well established that some trace elements (Sr and U, in particular) incorporated in the aragonitic skeleton of scleractinian corals provide a robust paleothermometer [*Beck et al.*, 1992; *Min et al.*, 1995; *Alibert and McCulloch*, 1997]. In a previous contribution [*Beck et al.*, 1997] we presented the progressive warming of the tropical southwest Pacific during the deglaciation based on analyses of corals drilled on Espiritu Santo, Vanuatu (15°40'S; 167°00'E). A 5-year section of an otherwise 47-year-long *Porites* colony revealed a large year-long cooling event dated at 4166±15 calendar years B.P. (U/Th date performed by W. Beck in the Department of Geology and Geophysics, University of Minnesota), which remained unexplained [*Beck et al.*, 1997]. This cold snap prompted us to analyze the entire colony in order to investigate whether this was a recurrent feature, and if so, whether strong ENSO events could be invoked as a possible cause for the cooling. In the present contribution we first look at the modern instrumental SST record from Vanuatu in order to characterize the ENSO signal in this area and then compare the modern SST and paleo-SST records.

2. Material and Method

We first collected a live *Porites* coral from Amédée Lighthouse, near Nouméa (New Caledonia) in 1992. The coral was slabbed, X-rayed, and cleaned in an ultrasonic bath prior to sampling. On average, 12 samples per year were taken continuously along the main growth axis using a dental burr and a three-axis positioning system. The aragonitic powder was then dissolved in 2% spiked nitric acid, and Ca, Sr, and U were analyzed with a Varian Ultramass inductively coupled plasma mass spectrometer (ICP-MS) following a new technique [*Le Cornec and Corrège*, 1997]. A coral sample from New Caledonia (labeled NC20) was reduced to powder, sieved with a 40-μm mesh, and used as a standard. Replicate analyses of NC20 yield an external reproducibility (2σ) of 0.05 mmol/mol for Sr/Ca (~0.7°C) and of 0.01 μmol/mol for U/Ca (~0.3°C). Sr/Ca and U/Ca analyses were fitted to the instrumental SST record from Amédée Lighthouse for the 1981-1990 period (Figures 1 and 2) using the Analyseries program [*Paillard et al.*, 1996]. Each tracer was then regressed against SST, and the regression yielded the following equations:

$$\text{Sr/Ca}\ (10^{-3}\ M) = 10.73 - 0.0657\text{SST} \quad R = 0.79,$$

$$\text{U/Ca}\ (10^{-6}\ M) = 2.106 - 0.0367\text{SST} \quad R = 0.89.$$

The precision (standard error of estimate) [*Runyon et al.*, 1996; *Bevington and Robinson*, 1992] calculated from these equation is ±1.3°C for the Sr/Ca thermometer and ±0.9°C for the U/Ca thermometer. This is slightly higher than the precision of the Sr/Ca thermometer using thermal ionization mass spectrometry which has been estimated to be ±0.3°C [*Alibert and McCulloch*, 1997].

The same procedures were used for the sampling and analyses of the fossil coral from Tasmaloum (Vanuatu). This coral was found between 0.80 and 1.20 m depth in drill core 9A,

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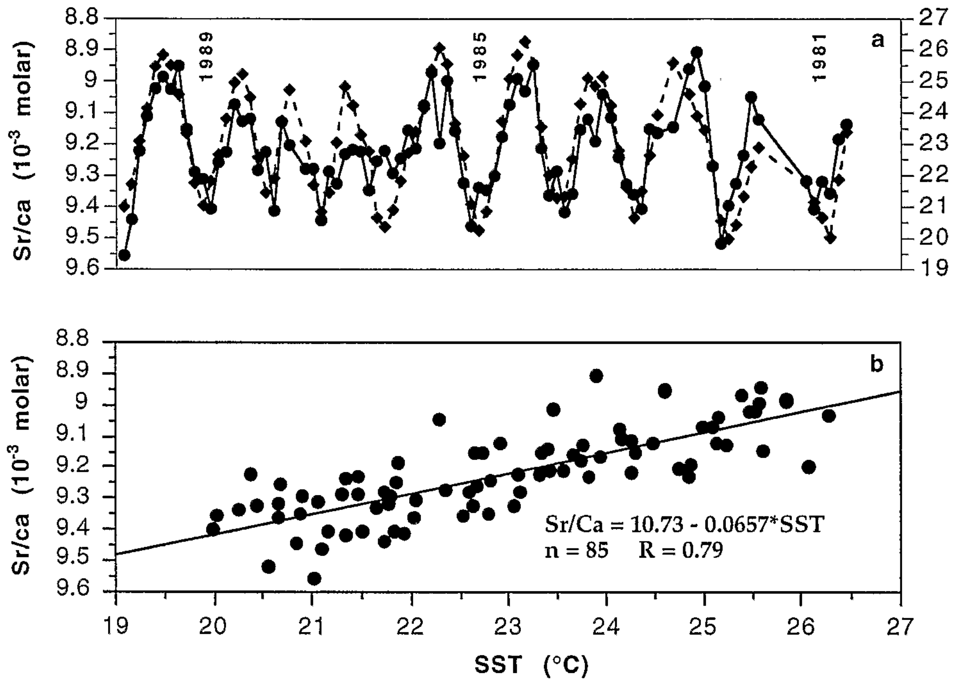

Figure 1. Calibration of the Sr/Ca thermometer in corals: (a) time series of SST (diamonds and dotted line) from Amédée Lighthouse (New Caledonia) and Sr/Ca (dots and solid line) from an adjacent *Porites* coral and (b) regression of Sr/Ca ratios against SST and the resulting equation.

collected at an altitude of +4.66 m above sea level [*Cabioch et al.*, 1998]. Owing to the calculated uplift rate the paleodepth of the *Porites* can be estimated ~ 10-15 m at 4150 years B.P. The surrounding coral assemblages indicate an open shallow marine environment (for details, see *Cabioch et al.*, [1998]). Sr/Ca and U/Ca analyses were converted to SST, using the abovementioned equations. In > 98% of the samples analyzed, Sr and U reconstructed SST agree well within

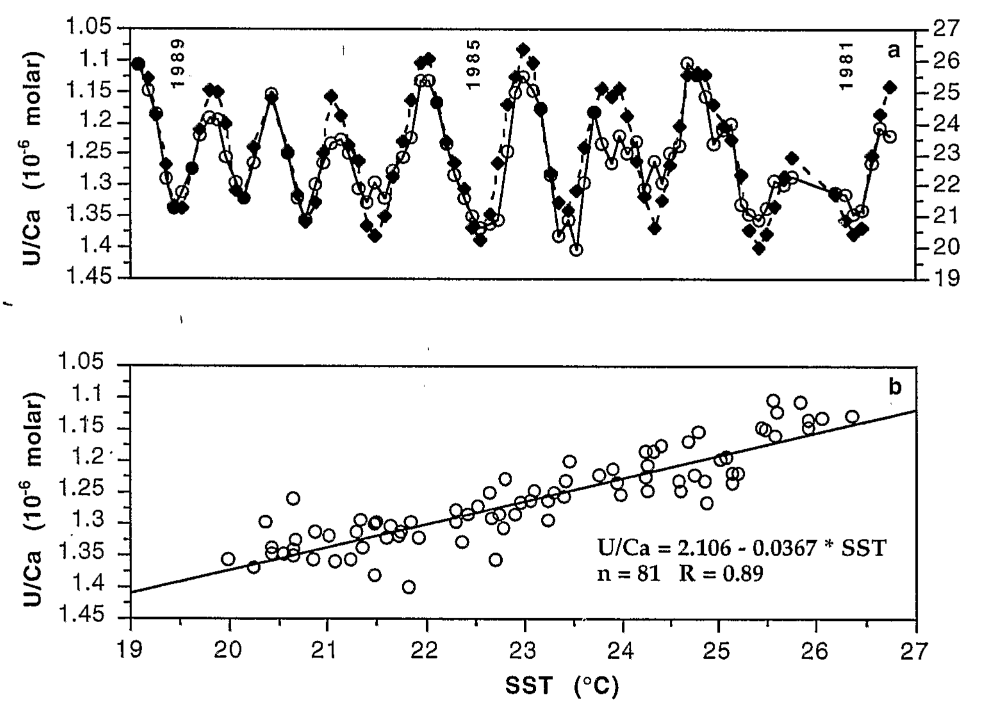

Figure 2. Calibration of the U/Ca thermometer in corals: (a) time series of SST (diamonds and dotted line) from Amédée Lighthouse (New Caledonia) and U/Ca (circles and solid line) from an adjacent *Porites* coral and (b) regression of U/Ca ratios against SST and the resulting equation.

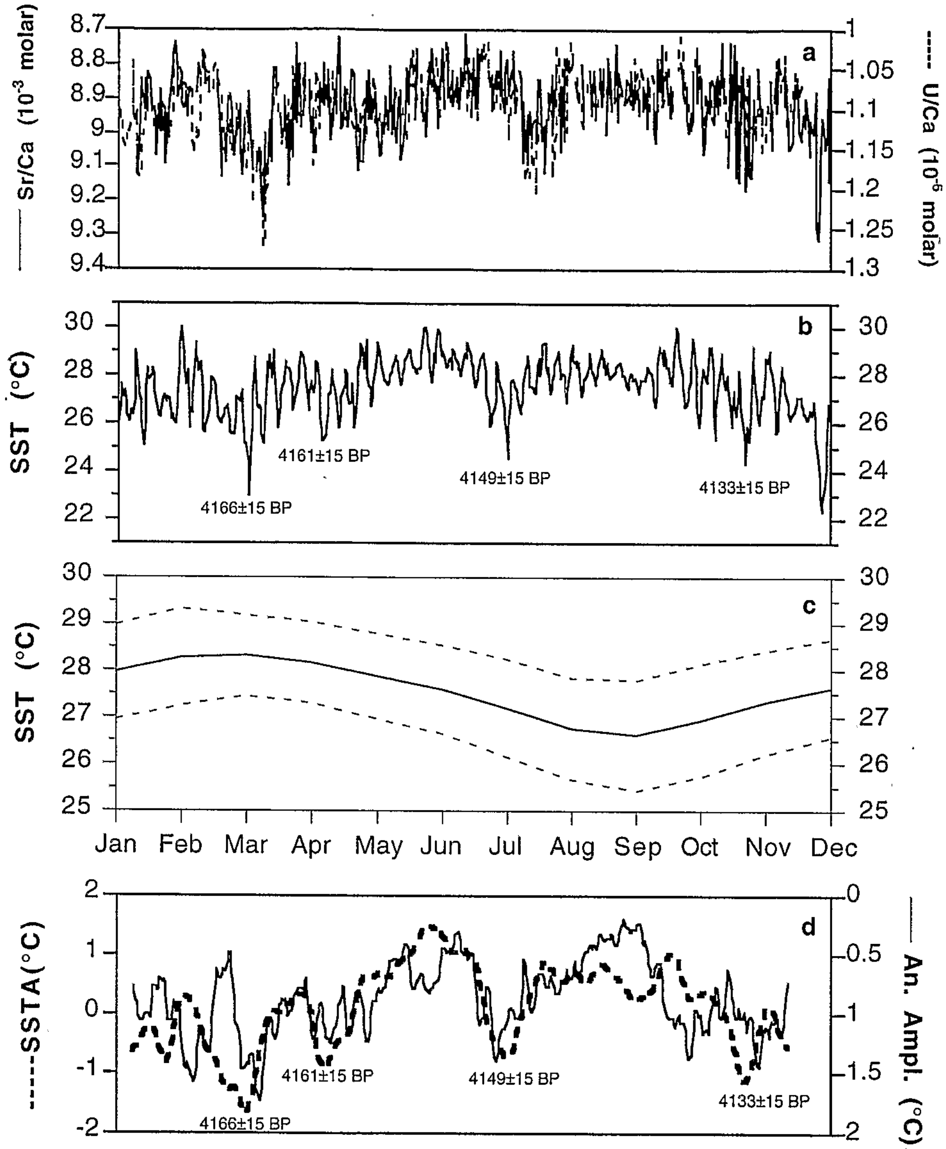

Figure 3. Mid-Holocene coral-derived SST data. (a) Raw time series of the Sr/Ca (solid line) and U/Ca (dashed line) data used to reconstruct the paleo-SST. (b) Composite SST record derived from the Sr/Ca and U/Ca analyses and resampled at monthly intervals. The ages are based on a U/Th date (taken from *Beck et al.*, [1997]). (c) Mean monthly SST (solid line) plus and minus the associated mean monthly standard deviation (dashed lines). (d) Monthly SSTA (dashed line) with respect to the 47-year period average SST (data are filtered with a 25-month Hanning filter) and 24-month running annual amplitude (solid line).

error. The potential effect of Sr/Ca change of seawater through time on the Sr thermometer in coral discussed by *Stoll and Schrag* [1998] does not appear to affect our Vanuatu record since there is a good agreement between the Sr and U reconstructed SST. A 47-year-long composite SST curve was then constructed, and monthly SST values were extrapolated using the Analyseries program (Figure 3)[1]

[1] Supporting data for Figure 3b are electronically archived at World Data Center-A for Paleoclimatology, NOAA/NGDC, 325 Broadway, Boulder, CO 80303. (e-mail: paleo@mail.ngdc.noaa.gov ; URL : http://www.ngdc.noaa.gov/paleo)

3. Modern Instrumental Record

The general surface circulation pattern in the southwest Pacific Ocean can be described as a large-scale anticyclonic gyre centered near 15°S [see *Delcroix and Hénin*, 1989, p. 791]. North of this latitude, a westward surface geostrophic flow tends to bring cooler water, whereas south of 15°S, an eastward flow carries warmer water. During an El Niño event the center of the gyre is shifted southward by few degrees of latitude, and Vanuatu is then affected by stronger than average westward flow [*Wyrtki and Wenzel*, 1984; *Delcroix and Hénin*, 1989]. Vanuatu is located on the southwestern fringe of the oceanic domain notably affected by SST changes associated with ENSO [*Delcroix*, 1998]. To assess the exact in-

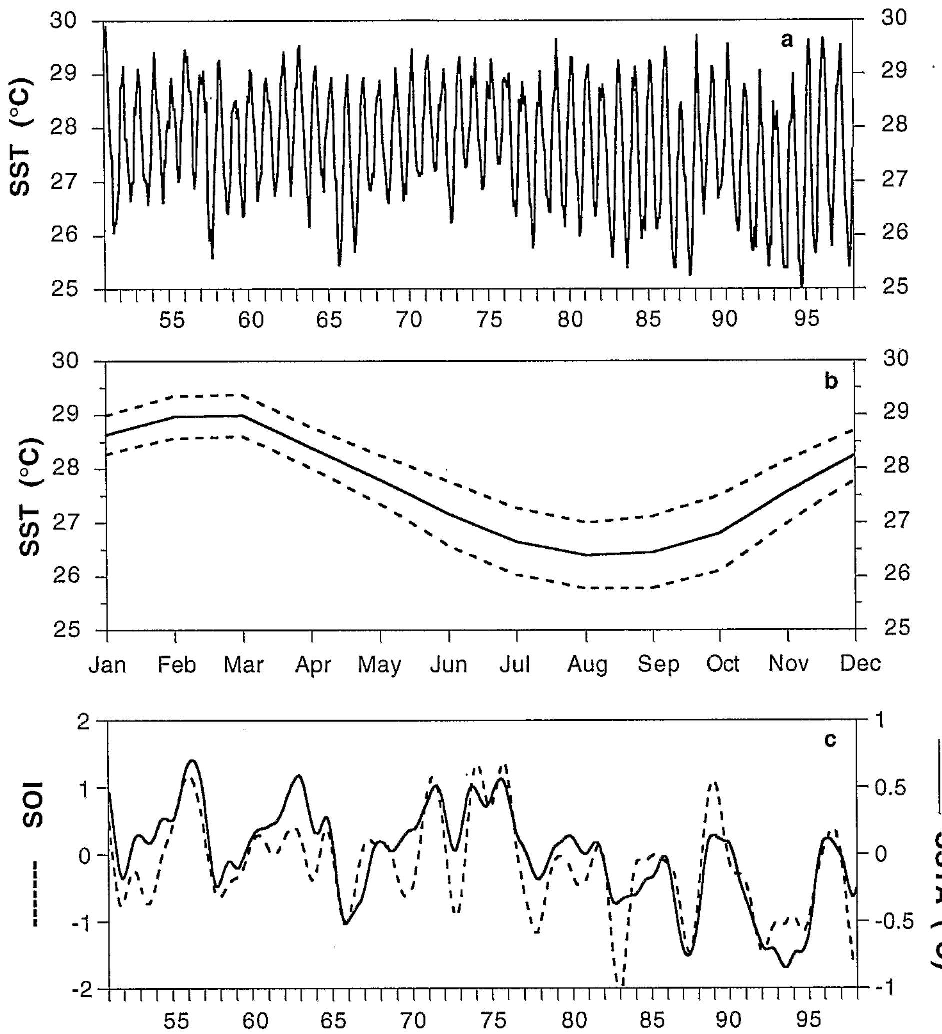

Figure 4. Modern Sea Surface Temperature (SST) data. (a) Monthly 1951-1997 SST for a 1° latitude by 1° longitude box centered on 16°S and 167°E, near Espiritu Santo, Vanuatu, SW Pacific Ocean. (b) Mean monthly SST (solid line) plus and minus the associated mean monthly standard deviation (dashed lines). This graph is plotted with the same scale as Figure 3c for comparison purposes. (c) Comparison of the Southern Oscillation Index (SOI; dashed line) with the monthly SST anomalies (SSTA; solid line) with respect to the 1951-1997 average (27.7°C). Both variables are filtered with a 25-month Hanning filter.

fluence of ENSO on this region, we first looked at the monthly 1951-1997 SST averaged over a 1° latitude by 1° longitude box containing Espiritu Santo [*Reynolds and Smith*, 1994] (Figure 4a). The mean SST for that period is 27.7°C, with a standard deviation of 1.1°C, an annual harmonic amplitude of 1.3°C, and an associated phase of 67°(Figure 4b). We applied a 25-month Hanning filter [*Blackman and Tukey*, 1958] in order to eliminate signals at periods of 1 year or shorter and clearly highlight interannual variations [see *Delcroix*, 1998, Figure 1]. The resulting filtered SST anomalies can then be compared to a filtered Southern Oscillation Index (SOI)(Figure 4c). The two signals are positively correlated (R= 0.80 at zero-month lag) and indicate that ENSO can account for ~64% of the interannual variance of SST. During the warm phase of ENSO [El Niño], SST tends to be colder in Vanuatu, consistent with stronger than average westward flow; sea level drops [see *Delcroix*, 1998, plate 5a], and so do the thermocline shoals, resulting in higher seasonal variability in SST at this latitude. During the cold phase of ENSO (La Niña), the deeper thermocline results in a weak seasonal SST amplitude.

Although quite high, the correlation between the SOI and the SSTA in Vanuatu clearly highlights the complexity of the coupled atmosphere/ocean system and the nonlinear response of SST to changes in the SOI. Spectral analysis of the monthly SST time series (using the Analyseries program [*Paillard et al.*, 1996]) indicate that significant peaks are present in the 2-4-year and 6.5-7-year bands, which are the classical ENSO period [*Enfield and Cid*, 1991]. Sea surface salinity (SSS, results not shown) anomalies also correlate well with the SOI, reinforcing our confidence that Vanuatu is a pertinent area to document ENSO variability through time.

4. Mid-Holocene Coral Record

The mid-Holocene SST record from Vanuatu also strongly exhibits ENSO-like periodicity. This paleo-SST record starts in 4175 ±15 B.P. and ends in 4128 ±15 B.P. (Figure 3). The raw paleo-SST were resampled at monthly intervals assuming that maximum SST occurred, on average, in March and minimum SST occurred in September as it does today (Figure 4b). However, the maximum of insolation at 16°S happened in November-December at 4150 calendar years B.P., compared to December-January today [*Berger*, 1978], and there is a possibility that the seasonal SST cycle was shifted 1 month backward. In spite of this probable small phase shift we have elected to present the annual harmonic cycle in the paleo-SST record as if it has the same phase as the modern record (Figure 3c). Over the 47-year-long period shown in Figure 3b, the mean SST is 27.6°C with a standard deviation of 1.2°C and an annual harmonic amplitude of 0.8°C (Figure 3c). This mean temperature is very similar to the modern 47-year regional average (27.7°C). Interestingly, the annual harmonic amplitude is somewhat smaller than the modern record (1.3°C). Parts of the paleorecord exhibit a seasonal range significantly larger than in the modern record, while in other portions the range is considerably smaller. A 24-month running annual amplitude (Figure 3d) clearly highlights the strong modulation of the annual cycle through time. This amplitude modulation explains the relatively large standard deviation observed in the paleorecord (Figure 3c). This large interannual variability is highlighted in the paleorecord by several long-lasting cooling events similar to the one at 4166±15 calendar years B.P. described previously [*Beck et al.*, 1997]. When passed through a 25-month Hanning filter, the fossil record yields interannual SST anomalies (Figure 3d) which are 2-3 times greater than seen in the modern period. The two records on Figure 3d are relatively well correlated, suggesting a common mechanism for these variations. Spectral analysis of the fossil SST record reveal periods in the 2-4 and 5.5-6-year bands, which are essentially the same as the dominant modern ENSO peaks.

5. Discussion and Conclusions

Comparison of the modern and fossil records emphasizes the stronger interannual variability which existed at circa 4150 calendar years B.P. Interestingly, this variability occurred at a time when the overall climate is thought to be very similar to the present-day one (same mean SST, similar solar radiation, and no ice volume effect). It is therefore important to determine whether the large interannual cooling events are caused by purely climatic (i.e., the ocean/atmosphere couple) or external factors. One possible external cause for cool SST are volcanic eruptions [*Bradley*, 1988]. The southwest Pacific and Vanuatu, in particular, are tectonically and volcanically active places [*Pelletier et al.*, 1998], and it has been shown recently [*Crowley et al.*, 1997] that coral-derived SST is a good recorder of volcanism. However, cooling events of the magnitude seen in our paleorecord at 4166, 4149, 4133 and 4128 calendar years B.P. (all dates given ±15 years; see Figure 3b) would require volcanic eruptions so large that their signature would certainly be found elsewhere around the globe (for example, the Pinatubo eruption in 1991 caused sea surface temperature anomalies (SSTA) of only 0.5°C in the Western Pacific Warm Pool [*Gagan and Chivas*, 1995]). In particular, sulfate peaks would be present in the polar ice core records. The detailed record of sulfate concentration in the Greenland Ice Sheet Project (GISP) 2 ice core [*Zielinski et al.*, 1994] only documents one peak at ~ 4157 calendar years B.P., which could correlate with either the 4166±15 or the 4149±15 B.P. cooling events. The other cold snaps, however, cannot be explained by volcanism.

By analogy to the modern instrumental record, it could then be argued that the fossil SST record documents a succession of long-lasting La Niña-like to average (i.e., SOI = 0) conditions, interrrupted by strong El Niño-like events. It is likely that during the mid-Holocene the southward (northward) shift of the large-scale anticyclonic gyre center during El Niño (La Niña) resulted in a shoaling (deepening) of the thermocline and a decrease (increase) of the annual amplitude in SST, as seen today. Still, the El Niño of 1982-1983 and 1986-1987 caused SST anomalies (filtered data) of the order of 0.5°C at Vanuatu. Cooling anomalies of 1°C or more, like those seen in the fossil record, imply large-scale oceanic changes not experienced in recent times. In particular, the strong modulation of the SST annual cycle would indicate that the depth of the thermocline and the associated zonal geostrophic circulation fluctuated more extensively than today on an interannual basis. The cause for these large fluctuations is unclear, but although the record is only 47-years-long, a visual inspection of Figures 3b and 3d clearly points to a decadal-scale variability. The three major cooling events (at 4166±15 B.P., 4149±15 B.P., and 4133±15 B.P.) are 17 and 16 years apart, respectively. The occurrence of a 14-17-year periodicity in Pacific coral oxygen isotopic records of the last centuries is now well established [*Dunbar et al.*, 1994; *Linsley et al.*, 1994; *Quinn et al.*, 1996]. On land, it has been identified in laminated sediments from an Ecuadorian lake [*Rodbell et al.*, 1999], where it shows maximum spectral density in the last 1000 years and between ~3000 and 4000 B.P., and in a global surface temperature data set [*Ghil and Vautard*, 1991]. However, reliable modern instrumental SST records are not long enough to fully document the interdecadal mode and its spatial distribution in the Pacific Ocean. Despite this limitation, several authors have proposed that the interdecadal mode could significantly modulate the ENSO cycle [*Holbrook and Bindoff*, 1997; *Latif et al.*, 1997; *Zhang et al.*, 1997; *Gu and Philander*, 1997; *Weaver*, 1999]. A recent simulation [*Weaver*, 1999] which used an extension of the delayed oscillator model showed that extratropical subduction of cooler water which propagates toward the equator [*Gu and Philander*, 1997] could alter ENSO on decadal to interdecadal timescales. This model generates SST time series for the eastern Pacific which mirror well our paleorecord, with significant changes in the seasonal amplitude through time. What we see in the fossil record could then represent phase shifts in the ENSO mode quite similar to those which occurred in the twentieth century [*Zhang et al.*, 1997] but perhaps with stronger exchanges between the tropics and extratropics.

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