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Keywords

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Coral microatolls from the central Pacific record late Holocene El Niño

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Abstract. Microatolls are discoid corals that have grown laterally because vertical growth is constrained by exposure at lowest tides. We demonstrate that a modern reef-flat *Porites* microatoll from Christmas (Kiritimati) Island preserves an oxygen isotope record of substantial sea surface temperature variations related to El Niño-Southern Oscillation (ENSO). We also show that a late Holocene fossil microatoll from the centre of the island contains interannual oxygen isotope variations over an approximate 20-year period. Three pronounced negative isotope anomalies attributed to warm El Niño events are superimposed on an annual cycle. El Niño events similar to those seen in recent decades appear to have been a feature of mid-Pacific climate in the late Holocene. Analysis of further microatolls offers a source of pre-instrumental El Niño tropical climate data. It may be possible to extend the NINO-C proxy to indicate intensity and frequency of ENSO over the past three millennia.

1. Introduction

El Niño and La Niña events are recurrent aperiodic variations in the equatorial Pacific driven by the windfield and movement of warm water in the central and eastern Pacific. They are strongly associated with the Southern Oscillation, reflecting pressure differences between the western and central Pacific. El Niño-Southern Oscillation (ENSO) events are quasi-cyclic with a typical periodicity of 2 to 7 years and have global teleconnections.

It has been suggested that the intensity and frequency of ENSO events may have changed as a result of anthropogenic influences such as an enhanced greenhouse effect [*Trenberth and Hoar*, 1996]. Two particularly intense (1982-3, 1997-8) and one especially 'persistent' (1990-5) El Niño occurred since 1970 [*Kerr*, 1999]. Climate models indicate increased frequency under future warmer conditions forced by elevated greenhouse-gas concentrations [*Timmermann et al.*, 1999]. While ENSO events are well documented in historical records, extension using multi-proxy paleoclimate data presently allows reconstruction back about 500 years [*Dunbar et al.*, 1994]. This is insufficient to effectively evaluate whether such unusual ENSO events might be within natural variability [*Dovgalyuk and Klimenko*, 1996; *Allan and D'Arrigo*, 1999]. The nature of mid- or late Holocene ENSO activity is largely unknown, although evidence from South America implies that fluctuations between warm (El Niño) and cold (La Niña) water offshore commenced around 5000 years ago [*Sandweiss et al.*, 1996; *Rodbell et al.*, 1999].

Geochemical analyses of massive corals provide valuable insight into past sea surface temperature (SST). Detailed reconstructions based upon oxygen isotope analyses can be used to reconstruct temperature at less than weekly resolution [*Gagan et al*, 1994], and precise sea surface temperature reconstructions can be cross-calibrated using the Sr/Ca ratio [*Beck et al.*, 1992; *McCulloch et al.*, 1996]. Modern corals provide reliable proxy records of ENSO sea surface temperature and rainfall throughout the Pacific [*Cole et al.*, 1993; *Tudhope et al.*, 1995; *Alibert and McCulloch*, 1997].

Fossil corals, though scarce and sometimes poorly preserved, provide an opportunity to extend the proxy record. It has been possible to demonstrate abrupt ocean warming in the early Holocene [*Beck et al.*, 1992], and mid-Holocene sea surface temperatures above present [*Gagan et al.*, 1998]. However, it is often difficult to determine water depth in which fossil corals grew, and it has not previously been possible to detect the intensity and duration of past ENSOs from fossil corals. Microatolls are discoid corals that have grown with predominantly lateral growth form at the reef-atmosphere interface, constrained in their upward growth by exposure at lowest tides. It has been demonstrated that central-Pacific *Porites* microatolls contain a low-resolution record of sea-level fluctuations related to ENSO when sliced and examined using UV fluorescence or X-radiography [*Woodroffe and McLean*, 1990]. We demonstrate here that modern microatolls from Christmas Island contain a reliable record of recent ENSO events and that a fossil coral microatoll contains an oxygen isotope record that records prehistoric El Niño events.

2. Field sampling and laboratory methods

Christmas Island is a large low-lying atoll fringed by a narrow reef flat. It has a central network of hypersaline lakes. The form of the island is controlled by Pleistocene limestones deposited during the last and probably previous interglacials, whereas the interior comprises a reticulate network of fossil coral (and associated biota) left emergent by a fall of sea level in the late Holocene [*Woodroffe and McLean*, 1998]. Christmas Island (157°30'W, 2°00'N) lies within the dry equatorial zone of the central Pacific and experiences particularly pronounced variations in SST, sea level and rainfall that are related to ENSO (Figure 1). It is an optimal site for paleoclimatic reconstruction of ENSO [*Fairbanks et al.*, 1997; *Evans et al.*, 1998b]. Monthly SST shows a low amplitude seasonal cycle of 1.3°C (minimum 26.6°C in

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February and maximum 27.9°C in June for the 1951-1980 period [*Bottomley et al.*, 1990]) on which El Niño warming and La Niña cooling are superimposed. Mean annual rainfall is 869 mm (1947-1991) but precipitation is high in El Niño years (3374 mm in 1987) [*Falkland and Woodroffe*, 1997].

We examined living microatolls around Christmas Island in June 1991 and found that their upper surface had responded to recent ENSO-modulated sea-level oscillations. Reef-flat microatolls recorded a lowering in the level to which coral polyps could survive associated with lower mean water levels towards the end of the El Niño events in 1983 and 1988. This resulted in concentric shallow depressions separated by low ridges on the microatoll upper surface similar to those observed elsewhere in Kiribati [*Woodroffe and McLean*, 1990]. One modern microatoll specimen (CW3) from just behind the reef crest at Northeast Point was subsampled for isotopic analysis. A vertical slab was also cut from one of the fossil microatolls (CW2) within the island interior.

Vertical slabs of modern and fossil corals were cut parallel to growth axis. Each slab was sliced to a thickness of 6 mm and preliminary X-radiography and UV fluorescence was undertaken. A ledge of 2 mm thickness was milled from the lower edge of the slice (at least 80 mm below the upper surface of the microatoll). After ultrasonic cleaning, samples were milled at 0.25 mm increments [*Gagan et al.*, 1994]. Every 4th or 8th sample was analysed to achieve approximately monthly sampling. Measurements were made on a Finnigan MAT-251 mass spectrometer using an automated individual-carbonate reaction (Kiel) device. Isotope ratios are reported as per mil (‰) deviations relative to V-PDB (Vienna – PeeDee Belemnite) and calibrated using National Bureau of Standards NBS19, with internal precision of 0.06‰.

3. Modern microatolls and SST

Figure 1 shows the $\delta^{18}O$ record of a modern *Porites* microatoll from Northeast Point from 1978 to June 1991. The isotope analyses show high reproducibility between adjacent samples. We have chosen a simple linear time model with an average extension rate of 18.5 mm yr^{-1} tied to surface morphology (sea-level depressions in 1983 and 1988). This time model is only a first-order approximation of growth rate, and minor changes in growth rate can be discerned between years from X-radiography and the spacing of primarily annual $\delta^{18}O$ cycles. Nevertheless, the chronology proposed in Figure 1 is sufficient to demonstrate the strong correlation between $\delta^{18}O$ and ENSO-related SST and rainfall.

Monthly SST values available from IGOSS (2° x 2°, centred on 157°30'W, 1°30'N) and monthly rainfall for Christmas Island are also shown in Figure 1. Warmer temperatures and higher rainfall in the El Niño years are clearly seen in the record. The microatoll grew on the reef flat continually flushed by water coming over the reef crest. We note that elevation of temperature on reef flats has masked the effectiveness of reef-flat corals in other settings [*Swart and Coleman*, 1980], but Figure 1 demonstrates that the ENSO record is well-preserved within the modern microatoll on Christmas Island. The oxygen isotope record shows a pattern of fluctuations ranging from –4.56‰ to –5.59‰, equivalent to a temperature variation of about 5°C, using a slope of 0.18-0.21‰ per 1°C [*Gagan et al.*, 1994]. This accords well with a maximum variation of 5.3°C observed in the IGOSS SST

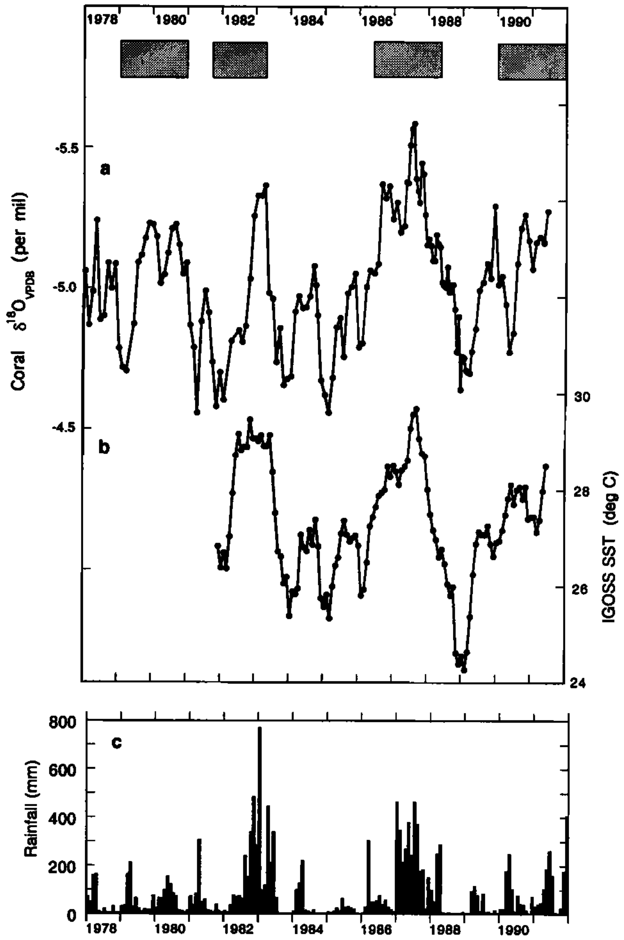

Figure 1. a) Time-series of $\delta^{18}O$ measurements through modern microatoll CW3. Periods with warm El Niño conditions, as shown by NINO3, are indicated by shaded blocks; b) IGOSS SST centred on 157°30'W, 1°30'N, 1981-1991; c) Monthly rainfall for Christmas Island 1978-1991.

data. There is a strong correlation between $\delta^{18}O$ and SST (Pearson correlation coefficient using linearly interpolated monthly $\delta^{18}O$, r = 0.80, 1991-1983, decreasing to r = 0.66, 1991-1981 as result of poorer fit of time model to pre-1983 coral). The 1987 El Niño and subsequent cool period are especially well recorded. However, the 1982-3 El Niño is relatively less pronounced and shorter lived than anticipated. This may result from stress or slower growth in the warmer water at that time coincident with lowering of the upper limit to growth seen in X-rays of banding pattern. It is inappropriate to apply deseasonalisation or to present the data as anomalies in view of the simple time model adopted and the short period of record. The modern microatoll clearly contains a record of variations in SST related to ENSO.

4. Late Holocene microatoll

Figure 2 shows $\delta^{18}O$ records from a slice through a fossil *Porites* microatoll (CW2) in the formerly more-extensive lagoon of Christmas Island [*Woodroffe and McLean*, 1998]. A conventional radiocarbon age of 2210±80 years BP (Beta 125321) has been determined for this coral which represents

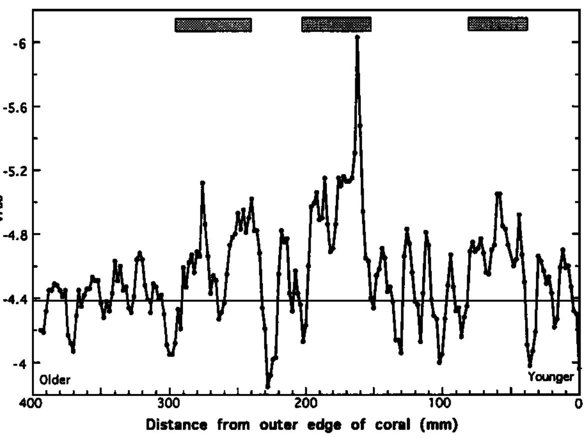

Figure 2. Oxygen isotope measurements through fossil microatoll CW2. Outer edge of coral (youngest) is shown to right. Seasonal variations are shown by the cyclical pattern and the record appears to span a period of 20-24 years. Mean of non-El Niño years (-4.38‰) is indicated by horizontal line, and periods of negative $\delta^{18}O$ anomaly attributed to El Niño-type events are shown by shaded blocks.

an age of around 1760±85 radiocarbon years BP when marine-reservoir corrected using a value of 450±35 years. The coral has not undergone diagenetic alteration. UV fluorescence and upper surface morphology indicate that it adopted a lateral microatoll growth form. A strong annual periodicity can be seen in the coral $\delta^{18}O$ record indicating that it grew at an average rate of around 20 mm yr^{-1}. However, whereas seasonal variations in SST have been found in many fossil corals from elsewhere, the record from this fossil microatoll from Christmas Island differs from the majority of fossil corals in that there are significant departures from the primarily annually-driven signature.

The initial (oldest) four years (395-293 mm) show low amplitude oxygen isotope variations (-4.05 to –4.68 ‰) implying an annual temperature variation of around 3°C. During a later period of regular seasonally-dominated variation (153-83 mm) the range was greater (-4.81 to –4.00 ‰) implying annual variation of around 4°C. However, of particular significance are three distinct El Niño-type events represented by significant negative excursions in the $\delta^{18}O$ values (291-235 mm, 199-155 mm and 81-41 mm). Each of these events appears to comprise at least two years of significantly warmer SST (and/or higher rainfall). The average for these periods is 0.3-0.6‰ more negative (1.5-3°C warmer) than the non-El Niño average (-4.38‰). Not only are the warmer parts of the year significantly anomalous during these periods, but the cooler season is also significantly more negative than non-El Niño years. Only in the first event did the cooler season exceed the non-El Niño average. These excursions are broadly similar in form to El Niño events that are recorded by the modern microatoll in the 1980s. The largest is considerably amplified by a very negative excursion (to -6.03‰) which presumably represents amplification of the SST-induced anomaly by a substantial rainfall peak. The effect of rainfall dilution may have been more apparent then than now as a result of a more extensive but poorly-flushed lagoon. The fossil record shows a stronger annual signature than the modern microatoll. It resembles isotope signals from modern and historic corals from the Galapagos Islands where there is a distinct seasonal variation of SST and ENSO events appear as persistent negative oxygen isotope anomalies lasting one or more years [*Dunbar et al.*, 1994].

5. Discussion

$\delta^{18}O$ of a massive *Porites* at 9 m depth off Southwest Point of Christmas Island has been analysed by *Evans et al.* [1998a], who demonstrated correspondence with SST. They showed a strong relationship between proxy ENSO records from a Christmas Island coral, which they called NINO-C, and the NINO3 index (for the area bounded by 150-90°W, 5°N - 5°S). On Tarawa, more than 3500 km to the west, it has been demonstrated that the oxygen isotope record in corals is primarily driven by salinity-dilution by rainfall, against which small sea surface temperature differences are secondary [*Cole et al.*, 1993]. On Christmas Island, *Evans et al.* have compared paired Sr/Ca and oxygen isotope measurements for 1981 to 1987 and indicate that the coral $\delta^{18}O$ is primarily recording sea surface temperature, with secondary salinity effects and a minor biological component [*Evans et al.*, 1998a; *Evans et al.*, 1999]. The difference between Tarawa and Christmas Island may reflect considerably lower rainfall on the latter. Our data indicate an amplitude of about 1‰ in coral $\delta^{18}O$ from the peaks of the 1987 El Niño to the 1988-9 La Niña which compares well with IGOSS SST change of 5.3°C and further substantiates that the signal is primarily responding to temperature at this site.

Sea surface temperature and rainfall-induced seawater $\delta^{18}O$ effects covary at Christmas Island during ENSO events; the coral $\delta^{18}O$ may therefore make a more appropriate climate monitor than either SST or seawater $\delta^{18}O$ (rainfall-related) anomaly alone. Coral from Christmas Island captures a large fraction of the variance associated with the thermal oceanographic signal of ENSO and the NINO-C proxy has been demonstrated to show significant teleconnections to regions of the Americas, Africa, Australia, India and Southeast Asia [*Evans et al.*, 1998a]. The modern microatoll $\delta^{18}O$ faithfully mirrors both the IGOSS SST record and the raw $\delta^{18}O$ from the coral in 9-m water depth (r = 0.65 between CW3 and 9-m coral, 1991-1983), though with a significant deviation (about 0.5‰ more negative than the latter).

The fossil microatoll grew amongst a flourishing shallow-water biota at least 50 cm above the height to which such organisms can presently grow [*Woodroffe and McLean*, 1998]. Mid-late Holocene sea level slightly higher than present has been widely recognised within the Pacific [*Grossman et al.*, 1998]. The fossil coral grew within the formerly more-extensive lagoon whereas the modern analogues grow on a reef flat continually flushed by open ocean waters. The oxygen isotope records compared between modern and fossil indicate a difference of around 0.5‰. This would appear to imply that present SST is significantly warmer than that experienced at the sea surface in the late Holocene. However, vital disequilibrium $\delta^{18}O$ offsets of 0.4‰ can occur between neighbouring coral colonies within a reef [*Linsley et al.*, 1999]. A similar 0.5‰ difference is also observed between the modern microatoll on the reef flat at Northeast Point, and the massive coral studied by *Evans et al.* growing at 9 m water depth off Southwest Point. Under these circumstances, it would be premature to attempt to calibrate the $\delta^{18}O$ to absolute SST. Nevertheless, the pattern of changes experienced in the paleo-lagoon in the late Holocene was evidently modulated by ENSO. Apparent lack of La Niña conditions in the fossil coral may be significant. However, the 1988-9 La Niña is prominent in the IGOSS SST records for this part of the Pacific (Figure 1) but was not especially marked in either the modern microatoll or the deeper coral. It would appear that Christmas Island corals may be less sensitive to La Niña events than to El Niño events.

Our results are especially significant for several reasons. First, we demonstrate that microatolls in very shallow water subject to periodic emergence of their upper surface during very low tides preserve records that can be reliably related to El Niño. These may be extended back as prehistoric proxies for ENSO. Second, we show that fluctuations similar to those associated with ENSO were occurring during the late Holocene. The fossil coral, growing under conditions of higher sea level in the late Holocene, appears to record El Niño events of comparable frequency and intensity to those experienced in the past two decades. Fossil microatolls, ranging in age across the past 3000-4000 years, occur at several interior sites on Christmas Island [*Woodroffe and McLean*, 1998], and are more accessible and easier to sample than fossil deeper-water massive corals. Detailed analysis of longer records from these mid-late Holocene microatolls, from this particularly sensitive site, offers the prospect of an insight into the natural variability of ENSO events, and a more extensive record of a NINO-C proxy of global significance.

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