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Monthly stable isotope records in an Australian coral and their correspondence with environmental variables

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Abstract. Monthly skeletal stable isotope measurements of a *Porites australiensis* coral from Abraham Reef, Australia, spanning the period from 1981 to 1991, are compared with monthly averaged SST (sea surface temperature) from satellite collected AVHRR (Advanced Very High Resolution Radiometer) and monthly downward surface short-wave insolation (SSI) measurements. We found that the $\delta^{18}O$ values varied as a function of the change in seawater temperature. There were anomalously high $\delta^{18}O$ values in coral that grew during the summer season of the three El Niño events 1982-83, 1987, and 1991. Advection of seawater with higher salinity (and higher $\delta^{18}O$ values) to our site or discrepancies between ocean skin temperature and mixed layer SST are likely reasons for the reduced resolution of $\delta^{18}O$-based SST. Increased coral $\delta^{13}C$ values occurred simultaneously with increases in SSI. During most El Niño events the maximum and minimum $\delta^{13}C$ values were lower than during normal years.

Introduction

El Niño events are associated with anomalous patterns of SST in the tropical Pacific Ocean including the eastward shift of the warm pool [*Meyers et al.*, 1986] coupled with dramatic changes in global climate and ocean circulation. El Niño events leave their imprints in the coral record. Although the basic relationship between regional SST and coral skeletal $\delta^{18}O$ is well established [*Wellington et al, 1996*] the influence of El Niño on seasonal stable isotope signatures in corals from the southwestern Pacific subtropical gyre has not been published. Previous work [*Gagan et al.*, 1994; *McCulloch et al.*, 1994] on Great Barrier Reef (GBR) corals show a strong salinity signal associated with El Niño conditions that are a consequence of reduced runoff because their corals grew within 30km of the Australian coast. Isdale [*Isdale*, 1984] reported yellow-green fluorescent bands in coastal GBR corals which correlate strongly with summer, monsoonal rainfall; there were no fluorescent bands in outer reef corals.

In this paper, we present monthly $\delta^{18}O$ and $\delta^{13}C$ values for a coral collected from the outer shelf (seaward edge) of the southern GBR and compare these results with monthly averaged SST and SSI measurements. Because our coral is 200 km offshore (Fig. 1) it can be used to study changes of the southwest Pacific subtropical gyre. Previously, Druffel and Griffin (1993) reported annual-to-biennial trends of $\delta^{18}O$, $\delta^{13}C$ and $\Delta^{14}C$ from this coral and discussed century timescale changes in the nature of El Niño that were apparent in these data. In order to understand short timescale environmental changes in the subtropical western Pacific, the seasonal variability of coral isotope records needs to be examined. Our purpose is to try to understand how subtropical corals record El Niño events and through what mechanism(s) El Niño events influence the coral records of the southwestern Pacific.

Methods

The *Porites australiensis* coral core was collected in May 1991 from Abraham Reef (22°6' S, 153°00'E) located in the Swain Reefs, in the southeastern GBR. A 6 mm thick slab was cut along the maximum vertical axis of growth. Each coral slab was x-rayed and mapped as described previously [*Druffel and Griffin*, 1993]. Twelve samples were sanded sequentially from the top edge of a leading high density (HD) band to the top edge of the following HD band, so one annual coral band produced 12 samples. A subsample from each homogenized, monthly coral sample was analyzed for $\delta^{18}O$ and $\delta^{13}C$ using a Finnigan 252 MAT light isotope ratio mass spectrometer in the laboratory of William Curry and Dorinda Ostermann at the Woods Hole Oceanographic Institution. Samples were crushed dry and reacted in orthophosphoric acid at 50°C. Uncertainty of the isotope measurements is $\pm 0.05‰$ for both $\delta^{18}O$ and $\delta^{13}C$, as determined by replicate analyses of several samples.

The SST record, derived from satellite collected AVHRR MCSST data contain weekly averaged SST values derived from the daytime and nighttime NOAA AVHRR. The data is available as a global data set (2048 x 1024 pixels) starting in Oct. 1981 (anon. ftp podaac.jpl.nasa.gov/pub/archive/mcsst) and are stored as HDF (Hierarchical Data Format software at

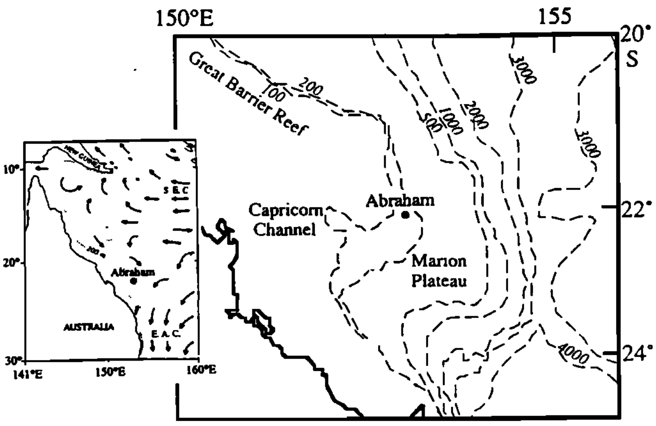

Figure 1. Depth contours of the southern Great Barrier Reef region (from *Merrifield and Middleton, 1994*). Inset: Mean circulation of surface currents in the Coral Sea and area further south during winter (Adapted from *Pickard et al., 1977*). The location of our coral site is indicated.

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anon. ftp.nasa.uiuc.edu/HDF/HDF4.ori/patches). Because the stable isotope data were from approximately monthly samples, we averaged the weekly MCSST data to obtain monthly records. We used SST data from 22°09'S,152°56'E, located 4km SW of the coral site. We also examined SST data at four other sites located 20-30 km from the coral site; data from the five locations agreed within ± <1.0°C.

The SSI information was acquired from satellite data collected through NASA. Monthly averaged Surface Radiation Budget short-wave radiation fluxes from July 1983 to June 1991 is available at the NASA Langley Research Center, and was obtained by ftp from the internet [*Darnel and Stayler*, 1996]. The spatial resolution of these data is 2.5° x 2.5°. We downloaded the monthly SSI at grid point 22.5°S, 152.5°E, 70km southwest of the coral site.

The ECMWF (European Center Median Weather Forecast) reanalysis meteorological dataset provided atmospheric temperature at 2m above the sea surface, net water budget (total precipitation minus evaporation) at the coral site, and the surface wind field 10m above the surface.

Results

The lowest monthly $\delta^{18}O$ values were aligned with the highest monthly MCSST values (Fig 2a) and the width of each annual band (data between two lowest $\delta^{18}O$ values) was adjusted using even time intervals to fit the MCSST data. Using this method, some of the $\delta^{18}O$ values were compressed in time and some were expanded. This represents a bias in the data because linear extension is not necessarily correlated with calcification or time. Nonetheless, this method is commonly used to align time-series because it captures the main coral features with sufficient chronological resolution [*Gagan et al.*, 1994; *McCulloch et al.*, 1994].

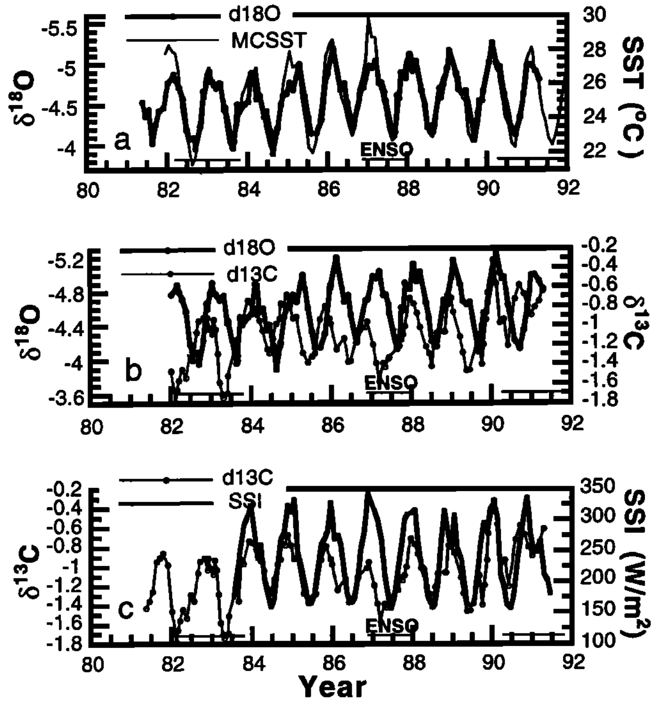

Figure 2. (a) Monthly coral $\delta^{18}O$ (solid circles) and monthly averaged MCSST values (°C, thin line) from our site, each plotted at the middle of each month; (b) Monthly coral $\delta^{18}O$ (solid circles) and $\delta^{13}C$ (open circles) measurements; (c) Monthly coral $\delta^{13}C$ (open circles) and monthly averaged downward SSI (W/m^2, thick line) from our site. El Niño events are indicted by horizontal lines. See text for details.

Differences between annual minimum and maximum $\delta^{18}O$ values ranged from 0.8-1.1‰, and those for SST ranged from 5-7°C (y-axis in Figure 2a is scaled using the relationship 0.22‰ per 1°C). The $\delta^{18}O$ and SST records overlap for the years 1988-1990. In 1982, 1985-87, and 1991, however, $\delta^{18}O$ values are not as low as expected during the maxima in SST. In addition, during 1982, 1985, and 1990, $\delta^{18}O$ values are not as high as expected during the SST minima. The largest discrepancies are apparent during the El Niños of 1982-1983, 1987, and 1990-1991 (marked with horizontal lines in Figure 2a). Since there are only 8 samples from 1985, anomalously low $\delta^{18}O$ values in the winter and high values in summer of this year are likely due to attenuation of the seasonal $\delta^{18}O$ signal.

There is an inverse correlation between $\delta^{18}O$ and $\delta^{13}C$, with a general lag of $\delta^{18}O$ values behind the $\delta^{13}C$ values during most years (Fig. 2b). The lag is lowest (1 - 3 months) for the period 1988-1990 and highest (5-6 months) for the summers of 1982, 1987, and 1991. The $\delta^{13}C$ trend follows SSI values except during the summers of 1987 and 1991 (Fig. 2c). $\delta^{13}C$ values were lowest during the El Niños of 1982-83 and 1987. To summarize, the most striking anomalies are the high $\delta^{18}O$ values during the summers of 1982, 1987, and 1991, and the low $\delta^{13}C$ values in 1982-83 and 1987 (Fig. 2).

Discussion

The $\delta^{18}O$ of coral skeleton is controlled by seawater $\delta^{18}O$ (i.e. salinity) and temperature-dependent oxygen isotope fractionation during accretion of aragonite. In scleractinian corals, field observations indicate that, on average, decreases of 0.18 - 0.22‰ in $\delta^{18}O$ correspond to a 1°C increase in SST [*Druffel*, 1985; *Dunbar and Wellington*, 1981; *Fairbanks and Dodge*, 1979; *Wellington et al*, 1996]. Our coral $\delta^{18}O$ values, interpolated from the measured values to obtain the same dates as for the MCSST data (and neglecting data of 1985), show a decrease of 0.16‰ per 1°C increase for non-El Niños (r=0.92), and 0.13‰ per 1°C increase for El Niños (r=0.95). This deviation from previous findings indicates that changes in water mass may be important for controlling $\delta^{18}O$ in our coral (see below).

The temperature effect on calcium carbonate $\delta^{13}C$ signature is too small to detect (-0.035‰ /1°C)[*Rubinson and Clayton*, 1969]. Instead, the three factors controlling coral skeletal $\delta^{13}C$ are: (1) ambient light levels; (2) heterotrophy; and (3) the $\delta^{13}C$ of dissolved inorganic carbon (DIC) in seawater [*McConnaughey*, 1989; *Cole and Fairbanks*, 1990; *Swart et al* 1996; *Grottoli and Wellington*, 1998; *Grottoli*, 1998]. Endosymbiotic photosynthesis depends on ambient light levels, which are mediated in a coral's environment by water depth and insolation. The higher the incident light, the higher the algal photosynthesis, removing ^{12}C preferentially from the DIC pool in the calcioblastic layer, leaving ^{13}C-enriched DIC for skeletal accretion. There is also evidence that skeletal $\delta^{13}C$

decreases with higher than normal light levels due to photoinhibition [*Grottoli-Everett,* 1998].

Four reasons are examined as possible reasons for the anomalous coral stable isotope patterns we observe during El Niños. First, the ocean's skin temperature (recorded by the AVHRR) could be higher or lower than underlying mixed layer bulk SST (recorded in the coral $\delta^{18}O$ record) due to intense insolation [*Kleypas and Burrage,* 1994; *Schluessel et al.,* 1987] or high evaporation [*Smith* 1996], respectively. The SSI (Fig. 2c) record shows that summer values during the years 1984 and 1986 are slightly higher than those for the period 1988-1990 by about 10-20 W/m^2 and highest in 1987. This intense insolation in the summer season may explain why the MCSST is higher than the coral $\delta^{18}O$ represented for the years 1984-1986. However, this explanation is inadequate to account for increases in $\delta^{18}O$ values in 1987 since the difference between skin temperature and bulk temperature should not exceed 1°C [*Schluessel et al.,* 1987]. Meyers et al. (1986) attributed the cooling of the western Pacific during the winter of 1982 to the anomalous meridional winds which induced more evaporation. This enhanced evaporation may, in part, have been responsible for the low skeletal $\delta^{18}O$ values during the winter of 1982.

Second, we calculated the seasonal accumulation (during rainy season December - February) of total precipitation minus evaporation over the area 17.5°-25.0°S and 150.0°- 155.0°E using daily ECMWF reanalysis data to determine if there was any correlation with anomalously high SST values at the coral site in 1982 and 1987. We calculated that the maximum $\delta^{18}O$ enrichment was less than 0.06 ‰ per month for the summers of 1982 and 1987 [*Wyrtki,* 1961; *Epstein and Mayeda,* 1953; *Dunbar and Wellington,* 1981]. This is small compared to the observed seasonal $\delta^{18}O$ enrichment of 0.5-0.6‰ (Fig. 2a). The influence of precipitation and evaporation is opposite in the year 1991 compared to the year 1987. Thus, local evaporation and precipitation are not the likely controlling factors for the offset of the coral $\delta^{18}O$ records with SST.

Third, we suspected that maximum linear skeletal extension of our coral might have decreased with increasing SST. Since large area SST data was not complete for our site due to cloud cover, we used atmospheric temperature instead. The contour of the atmospheric temperature 2m above the surface over the southwestern Pacific clearly demonstrates that the warm tongue (300°K) protrudes southward to 22°-25°S during El Niño years (e.g., 1982 and 1987) along the Australian east coast relative to its normal position at 18°-21°S during non El Niños (Fig. 3). This warm tongue results in anomalously high SST at Abraham Reef. Previous observations of reef-building corals from the eastern Pacific show that during periods of anomalously high SSTs, corals experience partial or complete loss of their endosymbiotic algae [*Druffel et al.,* 1990; *Glynn,* 1983]. We measured annual coral growth from the top of one high density band to the top of the adjoining band on 5 transects of the slab, and averaged these measurements for each year. Since our coral showed only a 3-4% decrease in linear growth rate during El Niño years (17.8 mm/yr) versus non-El Niño years (18.5 mm/yr), this suggests that cessation of skeletal accretion is not the reason for the high $\delta^{18}O$ values during peak El Niño warmings.

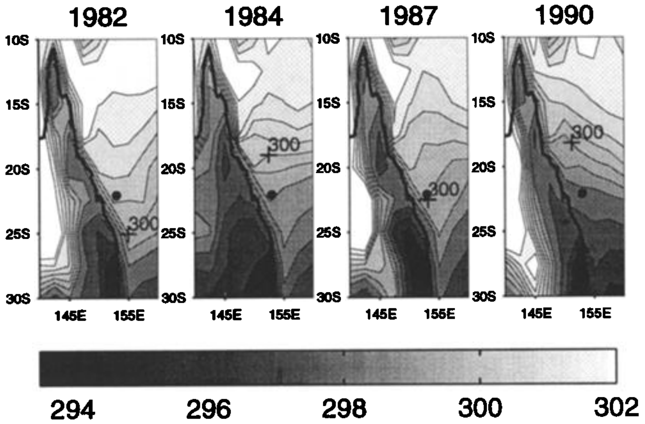

Figure 3. Annually averaged atmospheric temperature (°K) during January of four years at 2m above the surface over the southwest Pacific. The thick black line is the east Australian coastline. Note the diversion south of the 300°K isotherm over the GBR during the El Niño years of 1982 and 1987 and its northerly placement during the non-El Niño years of 1984 and 1990.

Finally, changes in advection and vertical transport in the South Pacific gyre during El Niño events may alter the watermass composition at our coral site and contribute to the observed coral stable isotope changes. It was shown that the westward South Equatorial Current (SEC) shifts south [*Donguy et al.,* 1984] and the slope of the thermocline in the center of the gyre decreases [*Morris et al.,* 1996] during El Niño events. Because the SEC originates in the divergence zone, its surface water typically has lower $\Delta^{14}C$ and lower $\delta^{13}C$ signatures than surface waters in the subtropics [*Druffel,* 1987; *Kroopnick,* 1985; *Rafter,* 1968]. Thus, advection changes contribute to low $\delta^{13}C$ and low $\Delta^{14}C$ signatures.

Other watermass changes related to El Niño events involve mixing layer and vertical mixing rate changes within the East Australian Current (EAC), the most prominent current off northeast Australia. When the EAC meets the Capricorn Channel, it drives a weak clockwise circulation causing upwelling on the Marion Plateau [*Kleypas and Burrage,* 1994]. Another source of upwelling is caused by the cross shelf intrusion due to eddies and meanders of the EAC. Intensified inflow of SEC waters during El Niño years enhances this upwelling [*Andrews and Furnds,* 1986]. Analysis of ECMWF data reveals that the prevailing wind field during the summers of 1981-1992 at our site is southeasterly, which discourages Ekman upwelling. However, during the summers of 1982 and 1987, the strength of the southeasterly trade winds at the coast decreased compared to average wind fields, enabling additional upwelling. Upwelling in the area of the western Coral Sea north of Abraham Reef occurs between 100 and 700 m depth with a maximum upwelling velocity at 150-200m [*Godfrey,* 1973; *Tranter et al.,* 1986]. Salinity rose from 35.0‰ at the surface to a maximum of 35.6‰ at 150m depth in the western Coral Sea [*Pickard et al.,* 1977]. A 0.6‰ salinity increase could impart a 0.35‰ maximum increase of skeletal $\delta^{18}O$, almost equal to our observed enrichments during the three El Niños (Fig. 2a).

Since our data shows a decrease in $\delta^{13}C$ during the El Niño events of 1982-83 and 1987, two reasons that may be controlling skeletal $\delta^{13}C$ in our coral are: (1) changes in the watermass sources to the coral site, bringing waters of lower $\delta^{13}C$ signatures [*Kroopnick*, 1985], or (2) photoinhibition due to higher than normal light levels on the coral [*Grottoli-Everett*, 1998] resulting from decreased sea level in the southwest Pacific during El Niño events.

Conclusions

In general, this study shows that: 1) $\delta^{18}O$ values decrease as temperature increases at a rate of 0.16‰ per 1°C at low to medium SST values (r=.92) and, 2) $\delta^{13}C$ values increase as SSI increases during normal years. During El Niño years, anomalies in $\delta^{13}C$ and $\delta^{18}O$ values were observed. Though the higher skin temperature relative to the subsurface bulk temperature of seawater could be responsible for the small $\delta^{18}O$ enrichment during 1984-1986, it is inadequate for explaining the large difference during the three El Niño summer seasons of 1982, 1987 and 1991. Increased upwelling of seawater with higher $\delta^{18}O$ values and lower DIC $\delta^{13}C$ values, likely contribute to the observed anomalies in coral isotope signatures at Abraham Reef.

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