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Reliability of coral isotope records from the western Pacific warm pool: A comparison using age-optimized records

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Abstract. Stable isotope analysis of two separate corals from Nauru Island in the warm pool of the western tropical Pacific confirm that coral oxygen isotopes are a robust recorder of environmental variables. Coral $\delta^{18}O$ faithfully records interannual variability even when strongly influenced by kinetic effects. Interannual to decadal variability of coral $\delta^{13}C$ remains enigmatic; only one of the two corals exhibits the expected light-$\delta^{13}C$ response in the interannual band. Coral $\delta^{18}O$ from this region has a great similarity to global instrumental temperature records reflecting the impact of the Pacific warm pool and variations of the Indonesian Low in concert with El Niño-Southern Oscillation on global climate. Since 1896, coral $\delta^{18}O$ has exhibited a cumulative decrease of 0.7‰, which reflects a combination of warming and more frequent El Niño events (precipitation) affecting the surface waters of this region.

1. Introduction

Intense surface heating along the equator, combined with the mean easterly flow of the trade winds, causes warm surface waters to accumulate at the western margin of the Pacific Ocean, producing sea surface temperatures in excess of 29°C and driving tropospheric circulation by creating deep convection aloft. Thus the western tropical Pacific plays an important role in the Earth's climate system through the export of sensible and latent heat [e.g., *Philander*, 1990; *Peixoto and Oort*, 1992]. On interannual and longer timescales, coupled air-sea interactions in the tropical Pacific have a large impact globally through atmospheric teleconnections (e.g., El Niño-Southern Oscillation (ENSO)). In order to ascertain natural variability relative to any potential anthropogenic imprint it is necessary to have sufficient records of key climatic variables such as temperature and precipitation. Continuous instrumental records are, in general, restricted to the latter half of this century, requiring the interpretation of climate proxy data such as that derived from biogenic archives.

The ratio of ^{18}O to ^{16}O ($\delta^{18}O$) in biogenic carbonates has been used as a paleothermometer since the pioneering work of *Urey* [1947], *McCrea* [1950], and *Epstein et al.* [1951]. *Weber and Woodhead* [1972] documented that although displaying genera specific offsets, the oxygen isotope versus temperature relationship of hermatypic (i.e., reef-building) corals is similar to that of the oxygen paleotemperature scale developed for mollusks [*McCrea*, 1950; *Epstein et al.*, 1951, 1953]. Thus coral $\delta^{18}O$ is a function of temperature and variations in the oxygen isotopic composition of water (δw). Coral $\delta^{18}O$ from symbiont bearing hermatypic corals is widely used in the documentation of modern interannual to centennial climate variability [e.g., *Cole and Fairbanks*, 1990] as well as in studies over much longer timescales [e.g., *Guilderson et al.*, 1994].

Unlike $\delta^{18}O$, interpretation of coral $\delta^{13}C$ is not as straightforward; nonetheless, it has been thought to be an incident radiation proxy [e.g., *Fairbanks and Dodge*, 1979]. Hermatypic corals that contain photosynthesizing endosymbiotic zooxanthellae exhibit light driven $\delta^{13}C$ variations. During photosynthesis the zooxanthellae preferentially utilize ^{12}C in the production of organic matter, leaving the carbon pool that is utilized by the coral to construct its skeleton enriched in ^{13}C [e.g., *Weber and Woodhead*, 1970; *Erez*, 1978; *Swart* 1983]. This "fractionation" or metabolic effect [*McConnaughey*, 1989a, b] results in the observed $\delta^{13}C$ depth distribution of *Monstastrea annularis* where individuals from shallower depths have higher ^{13}C (more light and increased photosynthesis) and those from deeper depths have a lower $\delta^{13}C$ as a consequence of the exponential reduction of light with depth (summarized by *Fairbanks and Dodge*, [1979]). *Fairbanks and Dodge* [1979] used the depth dependence of $\delta^{13}C$ as their model for light control and, as a test of their model, compared the seasonal structure of coral $\delta^{13}C$ with the proposed environmental control (radiant energy). The observed correlation between $\delta^{13}C$ and incident radiation, as well as the phasing between $\delta^{18}O$ (as temperature) and $\delta^{13}C$, supports the dependency of $\delta^{13}C$ on light. It would therefore be plausible to assume that decadal to centennial coral $\delta^{13}C$ time series reflects cloud variability.

A complication to the interpretation of coral stable isotope results is a relatively large kinetic effect associated with CO_2 hydration and hydroxylation reactions [*McConnaughey*

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1989a, b]. In this case, there is discrimination against molecules composed of the heavy isotopes ^{13}C and ^{18}O. Thus all coral isotope data are afflicted with a potential variable kinetic effect that can obfuscate the interpretation of long coral isotope records such that time-varying kinetic effects have the potential to mask or mimic external environmental controls.

In this study we test the reliability of secular trends in coral δ^{18}O and the consistency of coral δ^{13}C as an environmental recorder from two corals from the same reef in the western equatorial Pacific warm pool. We have generated two 42 year, high-resolution stable isotope time series from the two corals, and in order to test the consistency of coral δ^{13}C interpretations we have chosen to map the two records to a common timescale via their oxygen isotope records. Reliability of longer coral isotopic records is tested from the full length of the coral time series (~100 years).

2. Site Description and Methods

Nauru Island (166°E, 30'S), located within the warm pool of the western tropical Pacific, experiences minimal seasonal (≤1°C) and interannual (~2°C) sea surface temperature (SST) fluctuations [*Slutz et al.*, 1985; *Mangum et al.*, 1997; *Kaplan et al.*, 1998]. Because of its equatorial position, there is a twice annual passing of the sun and a concomitant biannual precipitation cycle with maxima in January (270 mm-month^{-1}) and July (160 mm-month^{-1}). Interannual variability dominates the precipitation cycle in concert with variations of the Indonesian Low. During "wet" years (synonymous with the ENSO warm phase), in excess of 4 m of rain can fall compared to half a meter during a dry (ENSO cold phase) year [*Baker et al.*, 1995].

Two large *Porites species* coral heads at 14 m bottom depth located offshore of the north side of the island were drilled in August 1995. The two colonies were separated by ≤ 20m. The cores (7.6 cm diameter) were cut into ~1 cm slabs, cleaned in distilled water, and air dried. No regions were infiltrated with boring filamentous algae or other organisms. Neither coral exhibited high-low density banding [e.g., *Knutson et al.*, 1972; *Buddemeier*, 1974]. The upper 750 mm of the first coral head (Nauru 1, *Porites australiaensis*, 1.8 m total length) were sampled sequentially along the major vertical growth axis at 1 mm increments with a low-speed drill, and the remaining

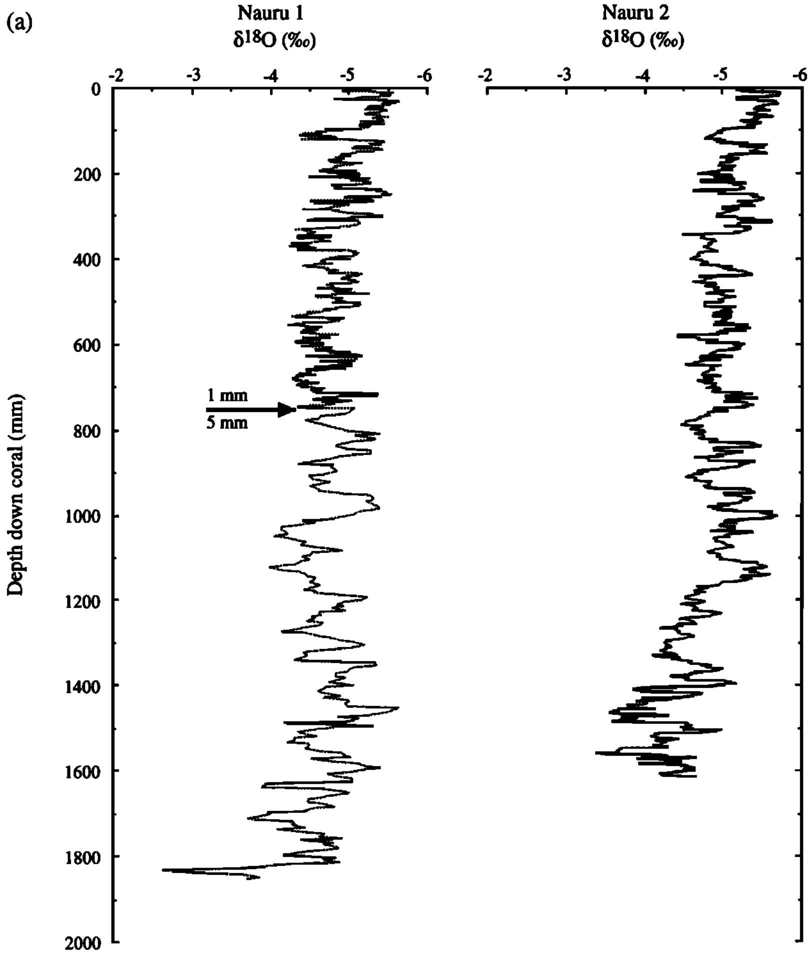

Figure 1. (a) Nauru 1 and 2 δ^{18}O as a function of depth down the coral core. The upper 750 mm of Nauru 1 was sequentially sampled at 1 mm increments, and the remaining section was sampled in 5 mm averages (arrow). The complete sequence of Nauru 2 was sampled at 2 mm increments. (b) Nauru 1 and 2 δ^{13}C as a function of depth down the coral core.

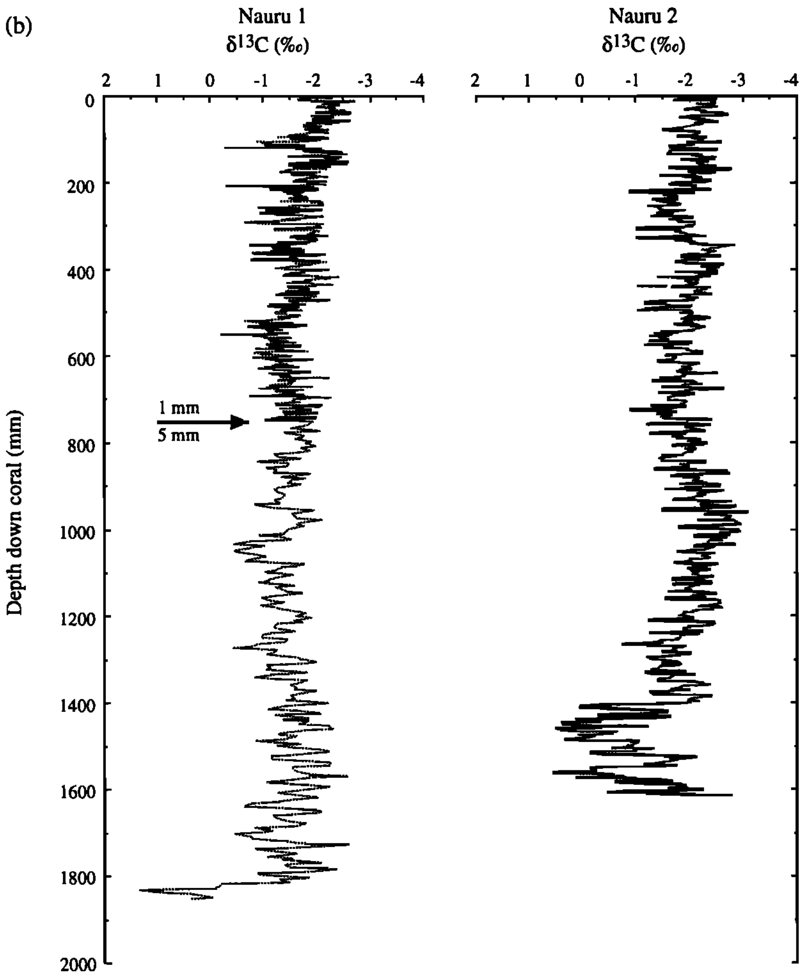

Figure 1. (Continued)

section was sampled in continuous 5 mm samples. Subsequently, it was determined that although still sampling the major vertical growth axis, sampling in the last ~20 cm deviated slightly from a track parallel to the coral axis. The second coral head (Nauru 2, 1.6 m total length) was sampled sequentially at 2 mm increments over its whole length. Samples (~1 mg) were reacted in vacuo in a modified autocarbonate device at 90°C and the purified CO_2 analyzed on a gas source stable isotope ratio mass spectrometer. Stable isotope data are presented in standard per mil notation relative to Vienna-Peedee Belemnite [*Coplen*, 1993] with an analytical uncertainty and reproducibility of ±0.05‰ (1-σ) as documented by an in-house homogenized coral standard. The $\delta^{18}O$ data have not been adjusted for the different acid fractionation factor between calcite (standards) and aragonite (sample).

Similar to previous studies [e.g., *Cole and Fairbanks*, 1990] we created a "preliminary" age model using the seasonal (doublet) structure of the respective $\delta^{13}C$ time series. The age model of Nauru 2 was then optimized through linear mapping of the coral $\delta^{18}O$ to the local precipitation record with an estimated error of ±2-3 months [see *Guilderson et al.*, 1998]. Over the interval where the two corals have similar sampling resolution (i.e., 1 and 2 mm density) the Nauru 1 $\delta^{18}O$ record was linearly mapped to the Nauru 2 $\delta^{18}O$ record. Age model construction for the complete time series followed a similar optimization procedure: a seasonal $\delta^{13}C$ age model followed by mapping $\delta^{18}O$ to the local precipitation record. Spectral analysis and/or filtering were performed on equal interval interpolated records using the "Arand" software package (P. Howell, personal communication, 1998). Records were detrended and the autocorrelation or cross-correlation functions were determined at one-third lag.

3. Results

Oxygen isotope results as a function of depth downcore (Figure 1a) show common features along the length of the two records, whereas carbon isotope results (Figure 1b) are disparate. The oxygen isotope results of the similarly sampled (high-resolution) sequences when placed on a common age scale (1952-1995) are consistent with each other, sharing 79% variance (Figure 2a). In general, the seasonal cycle is ~0.2‰, whereas interannual variability is as much as 0.7‰. Over this interval both records exhibit a trend of -0.11 to -0.14‰ per decade (Nauru 1 and 2, respectively), a

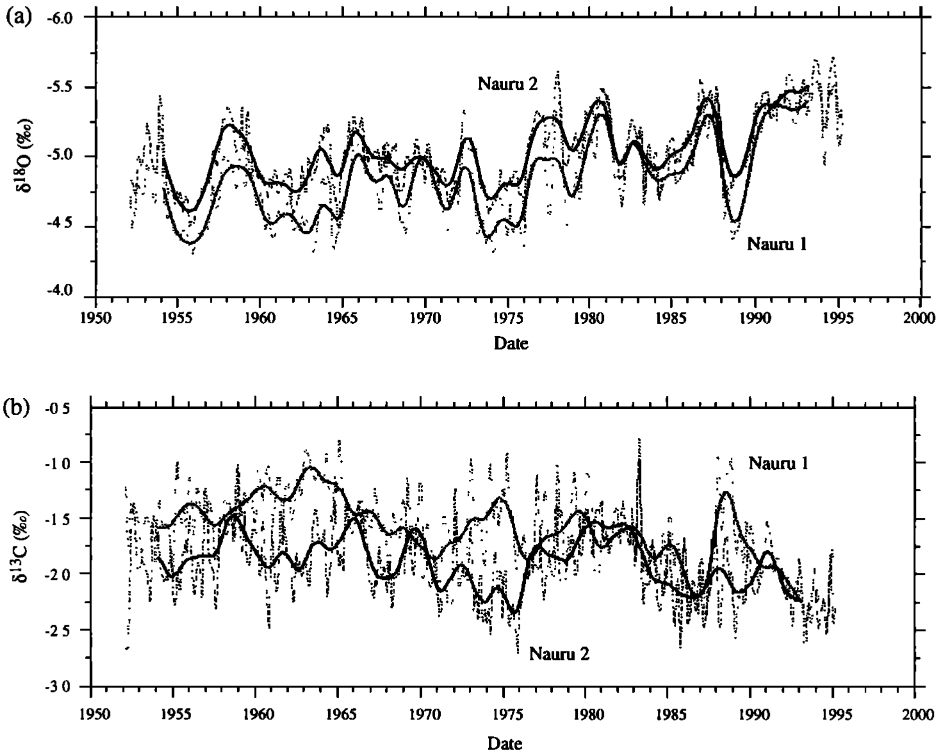

Figure 2. (a) Monthly Nauru 1 and 2 $\delta^{18}O$ on a common age scale as described in the text. Bold lines are the resultant records after low-pass filtering through a 25 weight Tukey-Cosine filter with a half amplitude of 2 years to remove seasonal variability. (b) Monthly Nauru 1 and 2 $\delta^{13}C$ on a common age scale as described in the text. Bold lines are low-pass-filtered records, similar to Figure 2a.

consequence of shifts toward more negative values in 1976 (-0.4‰ and -0.3‰, Nauru 1 and 2, respectively) and in 1990 (~ -0.2‰). There is a 0.2‰ offset in absolute value between the records; the Nauru 1 mean $\delta^{18}O$ = -4.86‰; and the Nauru 2 mean $\delta^{18}O$ = -5.06‰. Closer inspection shows that prior to ~1980, the offset is ~0.23‰, whereas post-1980 the offset is ~0.14‰ (Figure 3). On average, carbon isotopes are offset by ~0.3‰; Nauru 1 mean $\delta^{13}C$ = -1.63‰; and Nauru 2 mean $\delta^{13}C$ = -1.92 (Figure 2b), but this offset varies widely with time. There is a -0.15‰ per decade trend in the Nauru-1 $\delta^{13}C$ record (R^2 = 0.44), whereas there is a much weaker trend in the Nauru 2 $\delta^{13}C$ coral of -0.06‰ per decade (R^2 = 0.14), with no clear one to one correlation between the records (R^2 = 0.09). The correlation between the $\delta^{13}C$ time series does not increase with detrending, generating annual average values or Z score normalizations.

Oxygen (carbon) isotope values in the lowermost ~400 mm of the Nauru 2 record are ~0.5‰ (~1.5‰) higher than the

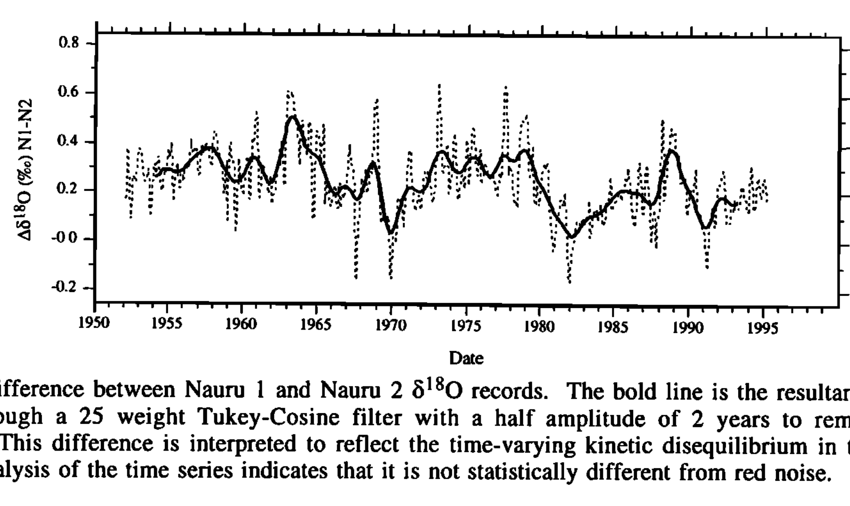

Figure 3. Difference between Nauru 1 and Nauru 2 $\delta^{18}O$ records. The bold line is the resultant record after filtering through a 25 weight Tukey-Cosine filter with a half amplitude of 2 years to remove seasonal variability. This difference is interpreted to reflect the time-varying kinetic disequilibrium in the respective records. Analysis of the time series indicates that it is not statistically different from red noise.

remaining upper section. Breaking this series into two sections results in two distinct data clusters in isotopic space. The lower section has a linear trend (slope = 0.35, and R^2 = 0.62), whereas the remaining sequence does not. Carbon isotope data in this lowermost sequence still exhibit an annual cycle, although the amplitude is much higher than that observed upsection in the coral. Only the bottom 50 mm section of Nauru 1 has isotope values that are higher than that upsection. The full sequence of the Nauru 1 coral, although not sampled at a constant density, exhibits a consistent correlation in isotopic space over the whole lifespan of the record. The lowermost 50 mm has a slope of 0.86 (R^2 = 0.86), and the upsection sequence has a slope of 0.52 (R^2 = 0.36).

4. Discussion

4.1 Oxygen Isotopes

Cross-spectral analysis of the common high-resolution $\delta^{18}O$ records confirms the graphical mapping of the age models; the records are coherent and in-phase. This occurs not only in the ENSO band, which dominates the signal of the individual records, but also in the nonoptimized seasonal band. The long-term trend observed in both records is also recovered. Using the linear extension rate as an albeit imprecise proxy for calcification rate, the Nauru 2 $\delta^{18}O$ has a correlation with extension rate, whereas Nauru 1 $\delta^{18}O$ does not. Moreover, the correlation is in the wrong sense with respect to growth rate disequilibria [*McConnaughey,* 1989a, b] and is due to a slight decrease in linear extension rate in the Nauru 2 coral over this time interval. Short-term offsets between the two coral series can be due to inaccuracies in the mapping of the respective records or to variable kinetic effects, but the mean offset must be due to species-specific offsets (which may reflect species-specific kinetic differences). The relative disequilibria between the two records is nearly constant and, on decadal timescales, not statistically different from red noise. We therefore interpret the secular $\delta^{18}O$ trend as reflecting an environmental change rather than a change in calcification-rate-driven disequilibria.

The observed $\delta^{18}O$ decrease that occurs between 1952 and 1995 (~0.5‰) equates to a ~2.5°C warming, an ~2‰ decrease in salinity [*Fairbanks et al.,* 1997], or some combination thereof. Instrumental and reconstructed SSTs of a slightly larger region [*Reynolds and Smith,* 1994; *Kaplan et al.,* 1998] do show an ~0.5°C increase which can only be partly responsible for the observed trend in the coral records. Moreover, the shift does not appear to be a consequence of a change in the isotopic composition of precipitation in the region [*Rozanski et al.,* 1992]. There is a regionally coherent increase in precipitation to the east of Nauru post-1976 as a consequence of more frequent ENSO events [*Morrissey and Graham,* 1996] and a general increase in temperature and moisture content of the lower troposphere [*Flohn et al.,* 1990; *Diaz and Graham,* 1996]. It is a reasonable assumption that the $\delta^{18}O$ shift in 1976 is reflecting this tropical phenomenon.

The observed dependence between $\delta^{18}O$ and $\delta^{13}C$ in the lowermost section of Nauru 2 is consistent with that observed in asymbiotic corals and in slower growing portions within a coral colony and is interpreted to reflect a stronger kinetic overprint during calcification [e.g., *McConnaughey,* 1989a, b]. We have corrected the oxygen isotope data (1600-1200 mm) for the kinetic effects using the observed relation ($\delta' = \delta^{18}O_m - (-3.94 + 0.35 \times \delta^{13}C)$) and normalized it with the resulting standard deviation of the zero mean series. The normalized data exhibit consistent features quite similar to those observed in the upper coral sequence. When compared to the instrumental data, the normalized $\delta^{18}O$ data indicate that there was a significant change in the linear extension rate at ~1200 mm. The implied growth rate in the lower section is ~8 mm-yr^{-1}, while that above averages ~21 mm-yr^{-1}. Although we can not explicitly use the absolute $\delta^{18}O$ values in this lower section, the interannual character that reflects changes in precipitation in concert with the position of the Indonesian Low and the state of the ENSO is still preserved (Figure 4a).

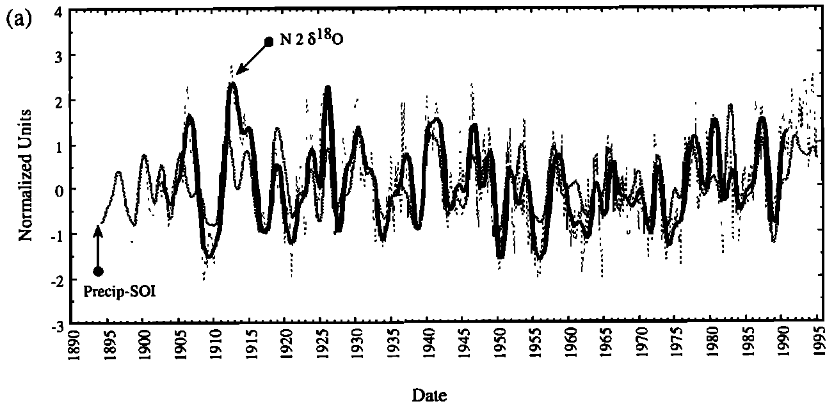

Figure 4a. Nauru 2 $\delta^{18}O$ (dotted) compared to the instrumental precipitation -Southern Oscillation record. The $\delta^{18}O$ data prior to 1939 have been corrected for kinetic fractionation using the observed relation between $\delta^{18}O$ and $\delta^{13}C$ as discussed in the text. To facilitate comparison, $\delta^{18}O$ and the instrumental record is plotted as a Z score normalization such that wetter or warmer conditions are positive. The precipitation-Southern Oscillation is a composite of the 1892-1977 Nauru precipitation record [*Baker et al.,* 1995] and the Tahiti-Darwin sea level pressure difference maintained by the Climate Diagnostic Center and has been passed through a Tukey-Cosine low-pass filter. The oxygen isotope data have also been passed through a similar filter.

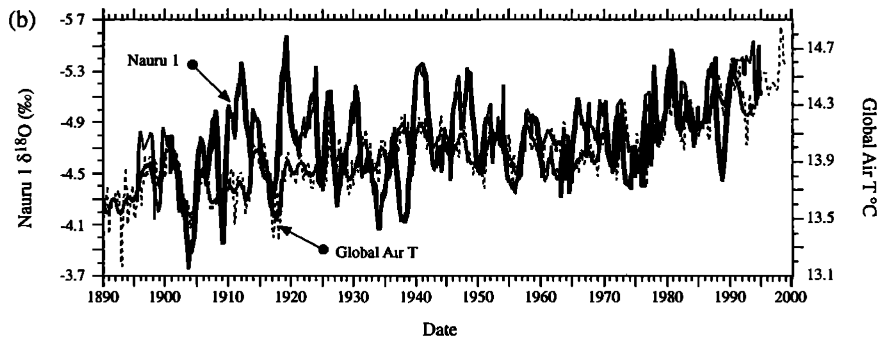

Figure 4b. Nauru 1 $\delta^{18}O$ (thin solid) and *Hansen et al.*'s [1996] global air temperature composite (dashed). Bold lines are the respective records passed through a Tukey-cosine low-pass filter with a half amplitude of 2 years. The two records share common interannual behavior.

Large kinetic effects do not appear to be a problem except in the lowermost 50 mm of the Nauru 1 sequence, and thus we can directly interpret the long-term trends over the length of the remaining record, 1895-1995 (Figure 4b). There is a long-term decrease of 0.04‰ per decade ($R^2 = 0.15$), which is the consequence of a weak decrease until the early 1960s followed by an accelerated decrease of nearly 0.2‰ per decade ($R^2 = 0.40$). The character of the Nauru 1 oxygen isotope record is similar to the Northern Hemisphere and global composite temperature records [*Jones*, 1994; *Hansen et al.*, 1996; and *Mann et al.*, 1998]. This is not surprising since climatic variations in this region are propagated into the mean state of the Earth's climate; the western equatorial Pacific surface ocean provides a heat source to the atmospheric boundary layer, and the associated deep convection exports sensible and latent heat to both hemispheres. The record shares nearly 20% variance with *Hansen et al.*'s [1996] global temperature record at zero lag, and is coherent and in phase in the annual, ENSO, and decadal periodicities. Similar results are obtained against Northern Hemisphere only records. During the warm phase of

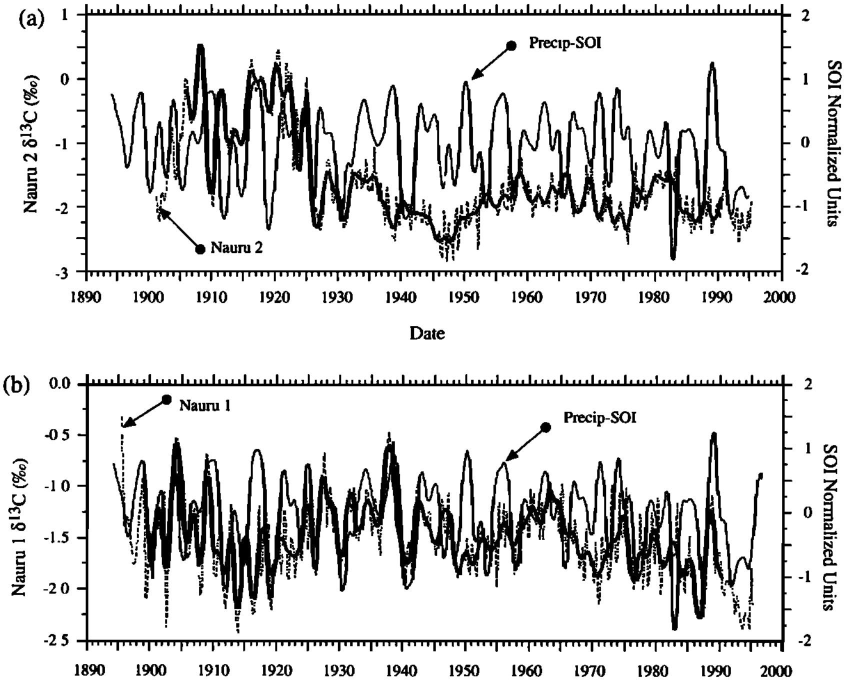

Figure 5. Coral $\delta^{13}C$ (dotted) as a function of time from (a) Nauru 2 and (b) Nauru 1 relative to the instrumental precipitation-Southern Oscillation record (thin solid line). The precipitation-Southern Oscillation record and the coral $\delta^{13}C$ records have been low-pass filtered to highlight interannual variability. The precipitation-Southern Oscillation data are in the same sense as $\delta^{13}C$; increasing cloud cover/rain and lower $\delta^{13}C$. Unlike the Nauru 2 coral, Nauru 1 $\delta^{13}C$ record follows the expected light-$\delta^{13}C$ model at interannual frequencies and contains an overall secular decrease consistent with the Suess effect.

ENSO, in excess of 20 million km^2 of the eastern equatorial Pacific anomalously warms, an area nearly equal to that of the "maritime continent" of the western Pacific. This has a dramatic effect on global temperatures; for example, the 1982 El Niño resulted in a ~0.4°C global anomaly [c.f. *Hansen et al.*, 1996]. Thus, during ENSO the isotopic variations in the Nauru 1 record reflect much more than a local or regional process.

4.2. Carbon Isotopes

The high-resolution δ^{13}C records from Nauru 1 and Nauru 2 fail to document a common interannual to decadal signal (see Figure 2b). Cross-spectral and band-pass filtering analyses document common frequencies in the two δ^{13}C time series, although they tend to be significantly out of phase. The carbon isotope data in the lowermost 400 mm of Nauru 2 (and lowermost ~50 mm of Nauru 1) still exhibit an annual cycle, although the amplitude is higher than that observed upsection, in addition to an increase in absolute values due to increasing kinetic effects (see Figure 1b). A singular δ^{13}C age model (e.g., using δ^{18}O to reconstruct precipitation a la *Cole and Fairbanks* [1990] could be derived for each coral record with relative errors of the order of 4-6 months. The lack of reproducible coherent δ^{13}C spectra from two coeval corals with similar growth rates casts doubt on interpreting interannual to decadal δ^{13}C as reflecting an external environmental variable (e.g., cloud cover) from only one coral record at this location.

At Nauru, increased precipitation (low coral δ^{18}O) would result in more cloud cover. In the light-δ^{13}C model, increased cloud cover would yield less photosynthesis, and the hypothetical carbon pool would have more ^{12}C in it. Calcification "tapping" this pool would therefore have lower δ^{13}C values. Of the two coral records the Nauru 1 record contains interannual variability in concert with the Southern Oscillation (Figure 5). Cross-spectral analysis of the oxygen (and the local precipitation-Southern Oscillation Index) and carbon isotope series confirms that the records are coherent and in phase in the ENSO frequency band and thus meets the expectations of a light-driven δ^{13}C model. It is tempting to interpret the ~0.6‰ δ^{13}C decrease over the length of the record and, in particular, the steeper decrease post-1965 as Suess effect [e.g., *Quay et al.*, 1992]. However, there remains enough uncertainty in the additional factors controlling coral δ^{13}C (e.g., pH and carbonate ion chemistry [*Hemming et al.*, 1998, and references therein]) that such an a priori interpretation is premature.

5. Summary

Stable isotope analysis of two separate corals from Nauru Island in the warm pool of the western tropical Pacific confirm that coral oxygen isotopes are a robust recorder of environmental variables. Small absolute value offsets are observed between two 42 year, high-resolution records, implying that coral δ^{18}O is an accurate, albeit perhaps not a precise, recorder of temperature or salinity changes. Coherent interannual and decadal features are recorded in both coral δ^{18}O time series. Local precipitation and SST anomalies at Nauru, indicative of the state of the Southern Oscillation, are faithfully recorded in coral δ^{18}O over the 100 year long time series of the two corals analyzed. Even "slow" growing sections of long corals, which are more strongly influenced by kinetics, appear to track effectively external environmental variables, although the absolute value cannot be used to estimate past SST or δw.

We observed a 0.7‰ decrease in δ^{18}O from 1895 through July of 1995, which occurs primarily as a small gradual decrease until 1976, a 0.4‰ shift in 1976, and an additional shift in 1990. The shift in 1976 toward warmer and wetter conditions is consistent with a suite of instrumental data documenting a change in the frequency and intensity of ENSO warm events over the last ~30 years. Interannual (ENSO) variability of the coupled ocean-atmosphere system conspires to reinforce its signature on coral δ^{18}O stable isotope records of the tropical Pacific. Because of the compounded impact of the Pacific warm pool and Indonesian Low, particularly on ENSO timescales, coral δ^{18}O from this region shares common features with hemispheric and global temperature records.

Coral carbon isotopes continue to remain enigmatic. The two records fail to document common interannual to decadal variability. Only one of the two coral δ^{13}C records reflected the light-level (cloud cover) interannual variability expected for this location. Without an a priori expectation (model) it would not be possible to determine which δ^{13}C time series appears to reflect more accurately external environmental variables. Although it is still possible to use seasonal δ^{13}C to construct an age model, interpretation of longer-term variability requires an independent check. The δ^{13}C time series that did exhibit the expected interannual variability also showed a decrease in mean δ^{13}C consistent with the Suess effect, whereas the other did not.

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