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Climatic trends and interdecadal variability from South-Central Pacific coral records

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Abstract. We study climate variability over interdecadal time scales from $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ records, measured in a *Porites lutea* coral core drilled in the Moorea lagoon. Previously, we demonstrated that the annual $\delta^{18}\text{O}$ variations reflect those in sea-surface temperature (SST), while the annual $\delta^{13}\text{C}$ variations record primarily cloud-cover changes. We apply two distinct spectral analysis methods to the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ time series from 1853 to 1989. Our analysis of the $\delta^{18}\text{O}$ record shows a secular warming trend and a 35-year oscillation in temperatures over the last 137 years. A trend and a 34-year cycle are also found in the $\delta^{13}\text{C}$ record. The latter trend may be caused by either anthropogenic effects or a cloud-cover increase in this region of the Pacific Ocean, while the interdecadal oscillation appears to be related to changes in cloud cover, as well as in precipitation.

1. Introduction and Motivation

Tropical ocean-atmosphere interactions play a worldwide role in interannual climate variability. These interactions undergo significant changes on decadal to centennial time scales. To follow and hence understand these longer-term changes, we have to extend the instrumental data with paleoclimatic records.

Stable-isotope records from corals have already been used to study climate variability in the equatorial [Cole *et al.*, 1993; Dunbar *et al.*, 1994] and southwest Pacific Ocean [Quinn *et al.*, 1993, 1998] on interannual to centennial time scales; not so for the central South Pacific. We have performed therefore $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ analyses of a 165-cm core from a massive head of *Porites lutea*, collected in the Moorea lagoon of French Polynesia (17°30'S, 149°50'W). Based on the resulting isotopic time series with a bimonthly resolution, Boiseau *et al.* [1998] studied the interannual climate variability in the central South Pacific from 1852 to 1989, and demonstrated that the annual $\delta^{18}\text{O}$ variations essentially reflect those in SST, while the annual $\delta^{13}\text{C}$ variations record those in cloud cover.

Advanced spectral methods permit us to decompose each isotopic signal into three coherent types of variability: a long-term trend, an interdecadal oscillation, and two interannual modes associated with the El-Niño/Southern-Oscillation (ENSO) phenomenon. The latter modes were

detected and described by Boiseau *et al.* [1998]. In the present paper, we study climatic variations in the central South Pacific on interdecadal to century time scales, based on the annual-mean $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ time series. The annual means are taken from July through June, and are nominally referred to the second of the two years involved; thus 1910 indicates the average of July 1909 through June 1910.

2. Isotopic Data and Spectral Methods

A colony of *Porites lutea* located off Moorea was drilled in 1990 [Boiseau *et al.*, 1998]. The analytical methods used to obtain the bimonthly $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values were presented in the earlier paper; the annual-mean time series studied here contain 137 yearly values each, from 1853 through 1989. Yiou *et al.* [1996] reviewed a number of advanced spectral methods for the analysis of such short, noisy data sets. We chose here the Multi-Taper Method (MTM) [Thomson, 1982] and Singular-Spectrum Analysis (SSA) [Vautard *et al.*, 1992], applied both to the annual $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ time series by using the SSA-MTM toolkit of Dettinger *et al.* [1995]. MTM works by applying an optimized set of fixed-shape tapers to our isotopic time series; we used 3 tapers and a bandwidth parameter value of 2. A discrete Fourier transform is then applied to the sum of the tapered signals to detect the sinusoidal modes contained therein. SSA permits us to separate each of our isotopic records into trend, oscillations, and noise components by diagonalizing the time series' lag-covariance matrix; the separation is obtained by projection onto this matrix's eigenvectors, which act as data-adaptive filters. The SSA window width used is 40 years, which is broad enough to capture the interdecadal climatic variations we are interested in here. Similar results are obtained with windows of 30 and 50 years.

3. Long-Term Variations in the $\delta^{18}\text{O}$ Record

For this coral core, Boiseau *et al.* [1998] demonstrated that the annual $\delta^{18}\text{O}$ is not affected by sampling resolution, extension rate, or calcification processes. Hence the isotopic variations shown in Fig. 1a as a centered and normalized time series reflect environmental changes in the Moorea lagoon. The coral $\delta^{18}\text{O}$ signal depends both on SST variations and changes of the seawater isotopic composition ($\delta^{18}\text{O}_{\text{water}}$). On this time scale, the $\delta^{18}\text{O}_{\text{water}}$ variations are controlled by the evaporation-precipitation balance. Our earlier study demonstrated that — for the 1958–1989 interval, for which instrumental SSTs are quite reliable — the

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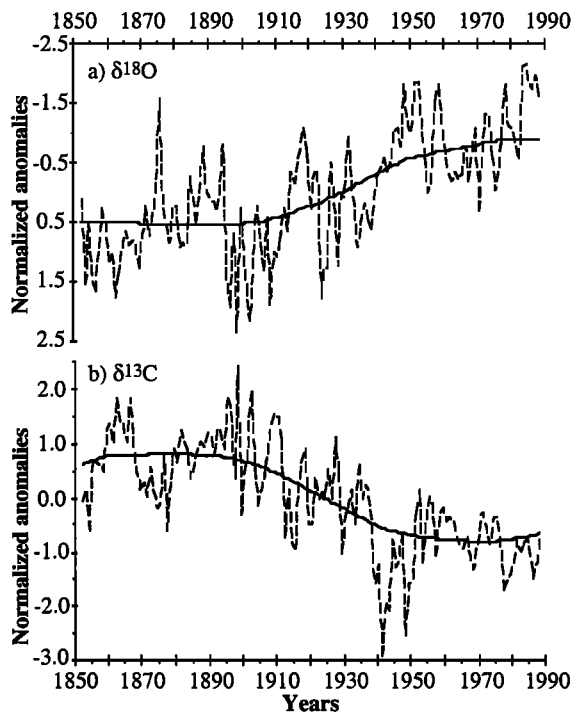


Figure 1. (a) Profile of $\delta^{18}\text{O}$ anomalies vs. time (dashed) and reconstruction of the trend (*i.e.*, projection onto the leading eigenvector) by SSA vs. time (solid), both from 1853 to 1989; negative $\delta^{18}\text{O}$ anomalies correlate with positive SST anomalies. (b) Profile of $\delta^{13}\text{C}$ anomalies (dashed) and reconstruction of the trend (same procedure as for $\delta^{18}\text{O}$) by SSA (solid); positive $\delta^{13}\text{C}$ anomalies correlate with decreased precipitation and cloud cover.

year-to-year variations of $\delta^{18}\text{O}$ are dominated by those in SST, rather than by hydrology. Assuming, as customary in the interpretation of proxy records for the pre-instrumental past, that this good $\delta^{18}\text{O}$ –SST correlation has not changed, interannual variations permit us to study SST variations near Moorea for the entire length of the $\delta^{18}\text{O}$ record. We applied MTM as well as SSA to the annual $\delta^{18}\text{O}$ time series. Both spectral methods extract three statistically significant types of variability: a trend, a 35-year oscillation, and two interannual-variability peaks (Fig. 2a). The latter two peaks, at 2.5 and 5.2 years, are related to ENSO's quasi-biennial and low-frequency modes [Rasmusson *et al.*, 1990], and were discussed by Boiseau *et al.* [1998]. We focus here on the long-term trend and the interdecadal variability.

The SSA's pure-trend component contains a major part of the variance (39%). This trend reflects a strong isotopic depletion in ^{18}O from 1853 to 1989 (see Fig. 1a). This depletion is not uniform over the last 137 years: the $\delta^{18}\text{O}$ values stay fairly flat from 1853 to 1910, while the coral skeleton is depleted rapidly in ^{18}O from 1911 to the end of the 1940s; from 1950 through 1989, the isotopic values continue to decrease at a very small rate (Fig. 1a). From the raw annual $\delta^{18}\text{O}$ record (not shown here), we calculate that the total ^{18}O depletion over the last 137 years is of 0.26‰ . According to the $\delta^{18}\text{O}$ –SST regression slope of Boiseau *et al.* [1998], this depletion corresponds to a temperature increase of $1.2 \pm 0.4^\circ\text{C}$, which is slightly higher than obtained for the

tropical Pacific Ocean by Smith *et al.* [1994], who statistically processed the sparse instrumental data. The nonuniform warming trend deduced at Moorea from the $\delta^{18}\text{O}$ data shows flat variations in temperature from 1853 to 1910, a rapid warming from 1910 to 1950, and progressive cessation of warming thereafter. Very similar changes in warming trend have been observed on a global scale by Ghil and Vautard [1991] and Mann and Park [1994].

The 35-year cycle contains 21% of the total variance in the $\delta^{18}\text{O}$ record. It is superimposed on the trend in (Fig. 3a) and reveals that the $\delta^{18}\text{O}$ minima (1882–1886, 1917–1921, 1949–1954, and 1985–1989) correspond to substantial temperature maxima, while the isotopic maxima of the interdecadal cycle (1861–1865, 1901–1905, 1932–1936, and

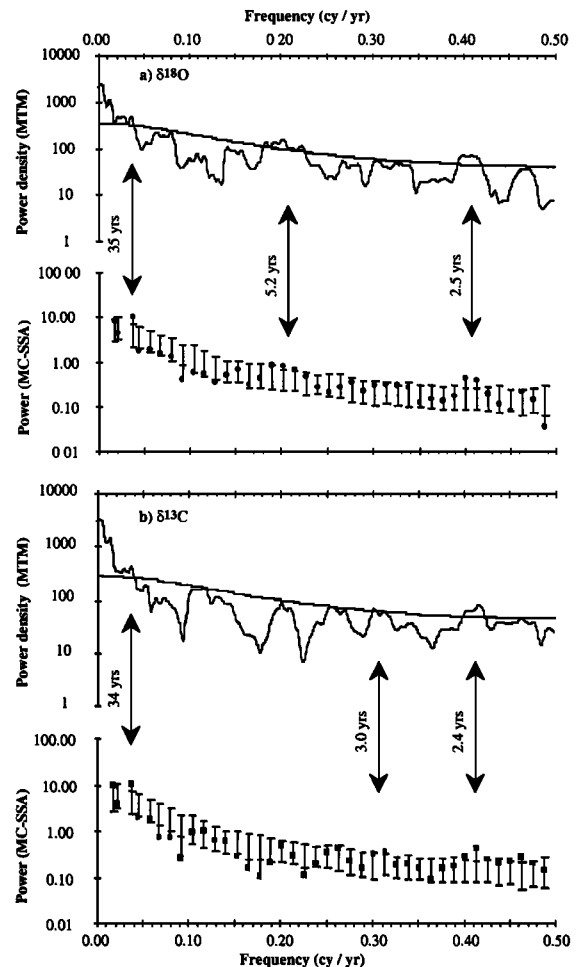


Figure 2. Spectral analyses by multi-taper method (MTM: upper plot) and singular-spectrum analysis (SSA: lower plot) of (a) the $\delta^{18}\text{O}$ record and (b) the $\delta^{13}\text{C}$ record. In the MTM spectra, the heavy solid lines give the power spectrum of the time series, while the light solid lines represent a 90% confidence interval with respect to a red-noise null hypothesis; in the SSA spectra, the confidence intervals are the 10% and 90% percentiles of Monte-Carlo simulations of a red-noise process with the same lag-zero and lag-one covariances as the time series. Components that fall within the confidence intervals are thus statistically indistinguishable from red noise, whereas the red-noise null hypothesis can be rejected when eigenvalues stand above the bars.

1968–1971) are associated with strong temperature minima. The 35-year oscillation has thus contributed to noticeably warmer and cooler multi-year spells in the central South Pacific Ocean over the last 137 years.

4. Long-Term Variations in $\delta^{13}\text{C}$

The profile of the annual $\delta^{13}\text{C}$ anomalies also exhibits a nonuniform trend over the last 137 years (Figs. 1b and 3b). This trend captures an even larger part of the variance than for the $\delta^{18}\text{O}$ profile (47% vs. 39%) and reflects a strong $\delta^{13}\text{C}$ depletion from 1853 through 1989, by 0.68‰ . From 1853 to 1890 the gradual changes in $\delta^{13}\text{C}$ are weak, from 1890 to the middle of the 1960s the decrease in ^{13}C is strong and persistent, while from 1976 on, the coral skeleton becomes slightly enriched in ^{13}C again.

Over the entire 1853–1989 interval, the total depletion of ^{13}C could have resulted from changes in cloud-cover patterns or dissolved inorganic carbon (DIC) in the seawater [Swart *et al.*, 1996]; it could also reflect anthropogenic effects [Quinn *et al.*, 1993]. Boiseau *et al.* [1998] reported that an annual-mean cloud-cover increase diminishes the algae's photosynthetic activity for that year; this in turn implies ^{13}C depletion in the coral skeleton deposited at Moorea during the same year.

Cloud cover has only been recorded since the 1960s at Tahiti, so we cannot compare its impact on coral $\delta^{13}\text{C}$ variability directly. Diaz *et al.* [1989] and Dai *et al.* [1997], however, deduced from adjacent land data a slight precipitation increase

in the tropical Pacific since the beginning of this century; this correlates presumably with an increase in cloud cover. On the other hand, there is no upwelling in the Moorea lagoon that could modify seawater DIC. Finally, Quay *et al.* [1994] have shown that, from 1970 to 1994, the $\delta^{13}\text{C}$ of DIC in the surface waters of the Pacific Ocean as a whole has decreased because of anthropogenic CO_2 that is isotopically enriched in ^{12}C . Consequently, we think that the coral $\delta^{13}\text{C}$ trend at Moorea is mainly caused by increased cloud cover and anthropogenic impacts. The relative influence of these two factors on the $\delta^{13}\text{C}$ signal cannot be distinguished by our current analytic methodology.

Both spectral methods also detect a coherent 34-year signal in the annual $\delta^{13}\text{C}$ values (Fig. 2b). This oscillatory component captures 12% of the total variance, somewhat less than for the $\delta^{18}\text{O}$ record. The reconstructed interdecadal oscillation (Fig. 3b) exhibits negative $\delta^{13}\text{C}$ anomalies below the data-adaptive, nonuniform trend, for 1870–1885, 1910–1923, 1938–1951, and 1967–1984. Using a land-based annual precipitation index over the 1892–1990 interval, Diaz *et al.* [1989] deduced a slight rainfall increase over the tropical Pacific in the 1890s, from 1910 to 1922, 1930 to 1935, 1942 to the end of the 1960s, and a stronger increase from 1970 on. Our 34-year oscillation in $\delta^{13}\text{C}$ seems therefore to be related to precipitation patterns near Moorea.

5. Concluding remarks

We studied climate variability over the last 137 years in the south-central Pacific Ocean from coral $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ records. Our spectral analysis of the time series of the annual-mean isotopic values suggests that climate variability here manifests itself as a nonuniform trend, on which interdecadal and interannual oscillations are superimposed. The long-term trend present in the annual $\delta^{18}\text{O}$ record reflects overall warming, while the large negative excursions of the 35-year oscillation describe warm spells from 1882 to 1886, 1917 to 1921, at the beginning of the 1950s, and from 1985 on. It cannot be excluded, though, that the salinity changes — besides those in temperature — could have affected the $\delta^{18}\text{O}$ record. A trend contained in the annual $\delta^{13}\text{C}$ record appears to be associated with both cloud-cover increase and anthropogenic perturbations, while the 34-year cycle in $\delta^{13}\text{C}$ seems related mainly to interdecadal precipitation variability.

The connection between precipitation changes and those in cloud cover at Moorea is not yet clear at this point. Boiseau *et al.* [1998] showed that the seasonal cycles of the two, averaged over the last 30 years, are well correlated. On the other hand, the local interannual variabilities of these two meteorological parameters are poorly correlated in the instrumental record at Tahiti [Rougerie *et al.*, 1985]. The interdecadal variability in $\delta^{18}\text{O}$ is also poorly correlated with that in $\delta^{13}\text{C}$ at zero lag (not shown); this suggests that possible variations in $\delta^{18}\text{O}$ —poor precipitation in the Moorea lagoon, as reflected by the $\delta^{13}\text{C}$ record, did not affect substantially the dominant effect of SST on the $\delta^{18}\text{O}$ for this time scale. On the other hand, the correlation between the two isotopic profiles equals 0.71 when $\delta^{13}\text{C}$ leads $\delta^{18}\text{O}$ by 6–7 years. This strong lag correlation at about one quarter of the 34–35-year period suggests an oscillatory mechanism that has freshwater fluxes in phase quadrature with SSTs.

Quinn *et al.* [1993] found at Espiritu Santo both a 15.4-

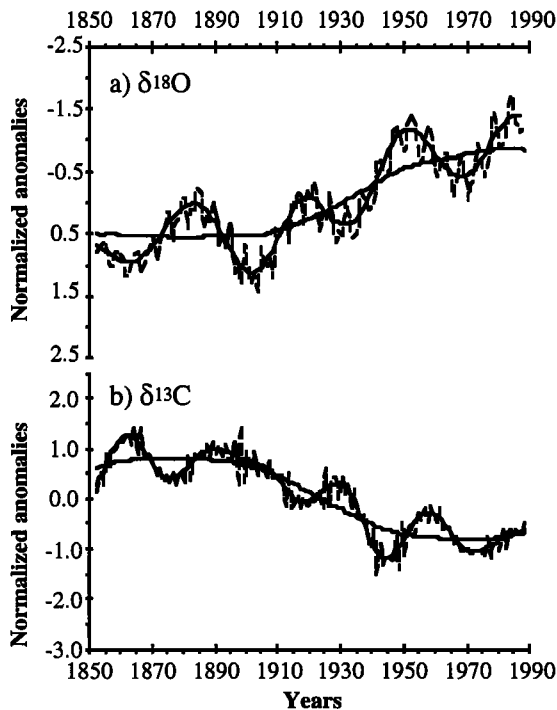


Figure 3. SSA reconstruction of the trend (light solid), interdecadal (heavy solid line), and interannual (dashed) oscillations found in (a) the $\delta^{18}\text{O}$ record and (b) the $\delta^{13}\text{C}$ record over the 1853–1989 interval.

year and a 33-year peak in their cross-spectral analysis of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, while Dunbar *et al.* [1994] found an 11-year and a 33-year cycle from a coral $\delta^{18}\text{O}$ record at Urvina Bay (Galapagos Islands). The latter authors related the 11-year peak to solar-cycle changes in insolation. This interpretation is controversial and, given the absence of this peak in the records of either Quinn *et al.* or our own, we shall not dwell on it here.

The 15-year peak corresponds to a global peak detected by Ghil and Vautard [1991]; its spatio-temporal aspects have been described further by Mann and Park [1994] and Plaut *et al.* [1995]. This 15-year peak seems, given the record's limited length, to be the harmonic of the 33-year one; it is not clear why its amplitude is too small for significant detection at Moorea. Cook *et al.* [1995] also found a 31-year peak in 2290 years of Tasmanian tree-ring data. Thus a stable, persistent oscillation with a period of 31–35 years seems to encompass the entire South Pacific for the last two millennia, and be characterized by a phase quadrature between SSTs and freshwater fluxes.

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