Interannual and decadal variability of the western Pacific sea surface condition for the years 1787–2000: Reconstruction based on stable isotope record from a Guam coral

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[1] We present a monthly resolved, 213-year stable isotope time series from a coral from Guam (13°N, 145°E), which is located on the northern edge of the western Pacific warm pool. Oxygen isotopic composition of the coral skeleton ($\delta^{18}O_{coral}$) shows seasonal, interannual, and decadal variability, which documents significant oceanographic changes related to thermal and hydrologic variations in this region. The $\delta^{18}O_{coral}$ anomaly reflects sea surface temperature (SST) anomaly and sea surface salinity (SSS) anomaly with significant r values of −0.69 and 0.49, respectively, which are strongly linked to oceanographic changes that occur during El Niño–Southern Oscillation (ENSO) warm and cool phases. We identified 46 ENSO warm (El Niño) and 53 cool phases (La Niña) in the coral record, which are consistent with those phases reconstructed by Niño 3.4 SST anomaly. Spectral analyses of the $\delta^{18}O_{coral}$ anomaly record for the years 1790–1999 identified significant peaks around ~3 to ~7 years. These results indicate that the Guam coral has recorded ENSO periodicity. The $\delta^{18}O_{coral}$ anomaly shows decadal variability of ~15- to ~45-year periodicity with significant shifts (<0.2‰) from warmer to cooler condition and vice versa. An accumulative decrease in $\delta^{18}O_{coral}$ time series may imply ~0.75°C warming of SST and ~0.23‰ freshening of seawater $\delta^{18}O$, corresponding to a decrease of SSS by ~0.85, in the northwestern tropical Pacific over the last 2 centuries.

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1. Introduction

[2] Tropical ocean-atmosphere interactions play a significant role in global climate changes on interannual and decadal timescales. Knowledge of past climate and ocean variability is crucial for understanding and modeling current and future climate trends. There are gridded sea surface temperature (SST) products that go back to 1870 or so, but the spatial and temporal instrumental climate records from the tropics, especially continuous time series before 1950, are scarce and limited. Thus there is a strong need for high-fidelity paleoclimate proxies that overlap with and extend beyond the instrumental records such as those derived from corals [e.g., *Cole et al.*, 1993; *Quinn et al.*, 1998], tree rings [e.g., *Briffa et al.*, 1998; *Mann et al.*, 1998], and ice cores [e.g., *Thompson et al.*, 1986; *Langway et al.*, 1995].

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[3] A massive hermatypic coral is an excellent paleoclimatic and paleoceanographic recorder because it commonly lives in shallow tropical to subtropical oceans, grows at a rapid rate (up to 2 cm/yr), and contains a remarkable array of geochemical tracers within its skeleton. In particular, oxygen isotopic composition of a coral skeleton ($\delta^{18}O_{coral}$) is a powerful tool for reconstructing past thermal and hydrologic variations in sea surface conditions [e.g., *Cole and Fairbanks*, 1990; *Tudhope et al.*, 1995; *Wellington et al.*, 1996] because $\delta^{18}O_{coral}$ variations are a function of both SST and $\delta^{18}O$ composition of seawater ($\delta^{18}O_{sw}$), the latter of which is commonly related to salinity [e.g., *Weber and Woodhead*, 1972; *McConnaughey*, 1989]. Long-lived corals have provided continuous time series of environmental variations in sea surface conditions over the past several centuries in many tropical regions, relating to changes in the state of El Niño–Southern Oscillation (ENSO), interdecadal linkages between the Indian and Pacific oceans, movement of the Intertropical Convergence

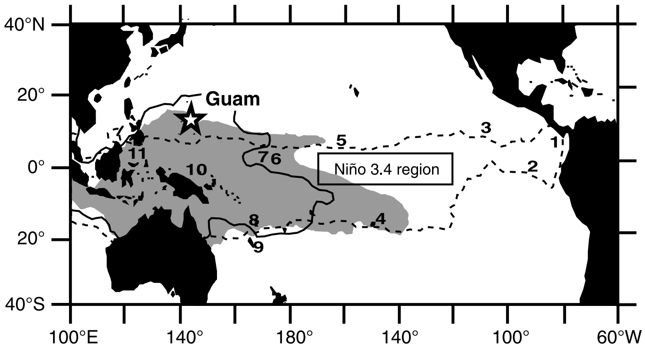

Figure 1. Map of the tropical Pacific Ocean. The numbers denote locations of other Pacific coral sites discussed in the text: 1, Secas; 2, Galápagos; 3, Clipperton; 4, Moorea; 5, Palmyra; 6, Maiana; 7, Tarawa; 8, Vanuatu; 9, New Caledonia; 10, Papua New Guinea; and 11, Bunaken. Note that the shaded area and the rectangular area show a region of the western Pacific warm pool with sea surface temperature (SST) of >28°C during non-ENSO phases and the Niño 3.4 region, respectively. A pair of 28°C isotherms for warm (dashed line) and cool (solid line) ENSO phases is also indicated.

Zone, the South Pacific Convergence Zone, and the western Pacific warm pool (WPWP) and the climatic effects of volcanic eruptions (see reviews of *Gagan et al.* [2000] and *Quinn and Tudhope* [2002]). However, most of the investigations using more than centennial or bicentennial coral records have been conducted in the regions of the eastern to central Pacific and equatorial to southwestern Pacific; there are few published long coral records in the northwestern tropical Pacific. The WPWP, a region of the highest SST of >28°C, weak trade winds, and deep atmospheric convection, has a significant influence on the global climatic system. The WPWP also influences tropical to subtropical Pacific climate and is dynamically linked with ENSO variability. Therefore it is of great importance to extend high-resolution oceanographic records in this region beyond the instrumental data based on long coral investigations.

[4] Here we present a monthly resolved, 213-year (the years 1787–2000) time series of carbon and oxygen isotope variations in a coral from Guam, which is located in the northern edge of the WPWP, to reconstruct significant thermal and hydrologic changes in the northwestern tropical Pacific over the last 2 centuries. The quantitative relationships between coral skeletal geochemistry and environmental variability at Guam for the years 1980–2000 have already been established [*Asami et al.*, 2004].

2. Material and Methods

2.1. Site Description

[5] Guam Island is located in the northwestern tropical Pacific (13°N, 145°E) (Figure 1). The study site, Double Reef (13°35′N, 144°50′E), located on the northwestern coast of Guam Island, is characterized by a narrow (<350-m-wide) fringing reef, extending >5 km from north to south. The coral community at this site is exposed directly to open sea surface conditions [*Asami et al.*, 2004].

[6] In Guam, Hadl 1.1 SST (the Met Office Hadley Centre's sea surface temperature) data derived from the British Atmospheric Data Centre show seasonal variations with a mean annual value of ~28.5°C for the years 1950–2000 and reach the annual maximum value between July and October and the annual minimum value between January and March. The maximum and minimum SST average 29.4° and 27.3°C, respectively. The amplitude of variations in Guam SST is rather small, ranging from 1.4° to 3.2°C with a mean value of ~2.2°C. The sea surface salinity (SSS) data from Etudes Climatiques de l'Ocèan Pacifique tropical (ECOP) of the Physical Oceanography Laboratory Institut de Recherche pour le Développement center document that the salinity reaches its maximum of 35.1 in July 1983 and its minimum of 33.9 in September and October 1971. The SSS shows indistinct seasonal periodicity with a mean value of 34.5 for the years 1969–1995. During ENSO warm phases (El Niño), SST and SSS are relatively cooler and higher in Guam, respectively, than those during non-ENSO and the cool phases (La Niña) in contrast to the central and eastern equatorial Pacific.

2.2. Coral Samples

[7] We collected a 273-cm-long core, GD2, from a hemispherical 3.3-m-high coral colony (*Porites lobata*) with a bottom depth of 7.8 m on 5 April 2000, using an underwater hydraulic drill with a 65-mm-diameter bit. This core was drilled vertically along the major axis of coral growth. This sample was slabbed to a thickness of 6 mm parallel to the axis of maximum coral growth. X-radiograph images were taken by MUJ-22FII (MG226/4.5, Yxlon International) under exposure conditions of 40 kV, 2.5 mA, and 2.0 focus with an exposure time of 45 s. X-radiographs showed highly regular and well-developed annual density bands (Figure 2). The GD2 dates back 213 years (1787–2000 A.D.) by counting annual density bands on the X-radiographs. We conducted scanning electron microscope observations (FE-SEM; JSM-6330F, Japan Electron Optics Laboratory) and X-ray diffraction analysis (X'pert PW3050, Philips) on skeletal fragments at intervals of ~10 cm to identify any nonskeletal mineral components. No evidence of diagenetic alteration of the coral was identified in the upper 270 cm below core surface (cmbcs), but acicular aragonite marine cements were identified in the lowermost part of the core (~270 to 273 cmbcs).

[8] In order to estimate annual extension rates of the Guam coral we measured variations in relative density along the sampling transects A and B (Figure 2) using an image analysis software (NIH Image) and then measured the distance from a maximum pixel density in a year to the maximum one in the next year. The annual extension rate was defined as the distance, corrected for the angles between sampling transect lines and skeletal density bands.

[9] Samples for stable isotope measurements were taken every 0.5 mm (weekly to biweekly sample resolution) for the years 1970–2000 and every 1 mm (approximately monthly sample resolution) for the years 1787–1969 along sampling transects A and B (Figure 2). The overlap of

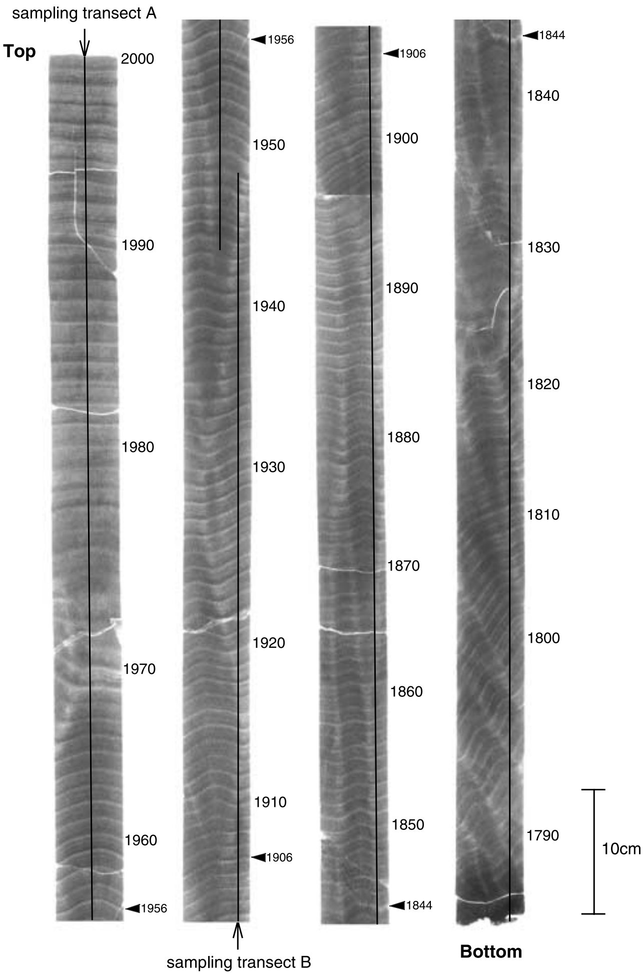

Figure 2. X-radiograph image of coral skeletons (*Porites lobata*). The well-developed growth bandings composed of alternating high-density (dark) and low-density (light) bands are observed. Isotope results are reported for samples extracted along sampling transects A and B.

~4 years between transects A and B allows a continuous coral isotope record.

2.3. Stable Isotope Analysis

[10] Stable isotope analyses were performed using an automated carbonate device (Kiel III, Finnigan MAT) attached to a Finnigan MAT Delta S mass spectrometer at the Institute of Geology and Paleontology, Graduate School of Science, Tohoku University, and a device attached to a Finnigan MAT 252 mass spectrometer at Technology Research Center/Japan National Oil Corporation, which is Japan Oil, Gas, and Metals National Corporation at present. Isotopic analysis follows *Asami et al.* [2004]. Isotopic ratios were reported in the conventional δ notation relative to Vienna Peedee belemnite and were calibrated to NBS-19 international standard after correction for ^{17}O interferences using the equations of *Santrock et al.* [1985]. Precision through a whole isotope analysis procedure deduced from daily replicate measurements of an internal laboratory calcite standard was better than 0.02‰ for δ^{13}C and 0.03‰ for δ^{18}O ($\pm 1\sigma$). Although coral skeletons are composed of aragonite, the oxygen fractionation factor (1.01025) at 25°C for calcite [*Friedman and O'Neil*, 1977] was adopted.

2.4. Coral Chronology

[11] We converted stable isotopic values from the depth domain to the time domain by the following procedures. First, a calendar year was assigned to a single pair of high- and low-density bands. Second, for the years 1951–2000, maximum and minimum $\delta^{18}O_{coral}$ values in a given year were assigned to minimum and maximum SST (HadI SST) in the year, respectively. Since SST generally recorded the highest values in July–September and the lowest values in January–March, maximum and minimum $\delta^{18}O_{coral}$ values in a given year were assigned to February and August for the years 1787–1950, respectively. Subsequently, the other isotopic values were plotted by linear interpolation between the fixed points.

2.5. Spectral Analysis

[12] In this study, a cross-spectral analysis was performed using the ARAND package developed for the Spectral Mapping (SPECMAP) project and provided for the use on personal computers by P. Howell (Brown University). The standard procedures are detailed elsewhere [*Jenkins and Watts*, 1968; *Imbrie et al.*, 1989].

[13] For a spectral analysis we used the multitaper method (MTM) that is contained in the SSA-MTM toolkit, a set of programs developed by the Atmospheric Science Department, University of California, Los Angeles (available at http://www.atmos.ucla.edu/tcd/ssa). The program presented by M. Mann is a version of the nonparametric MTM method developed by *Thomson* [1982, 1990a, 1990b] and produces confidence intervals [*Mann and Lees*, 1996]. The details of this technique are available in the SSA-MTM toolkit documentation.

[14] Wavelet analysis is a useful tool for analyzing time series with many different timescales and/or changes in variance. We performed a wavelet analysis using the Morlet wavelet, consisting of a plane wave modulated by a Gaussian. In this study, the nondimensional frequency was taken to be 6 to satisfy the admissibility condition [*Farge*, 1992]. The wavelet software was provided by C. Torrence and G. Compo (available at http://paos.colorado.edu/research/wavelets/). Further information on the wavelet analysis is provided by *Foufoula-Georgiou and Kumar* [1995] and *Torrence and Compo* [1998]. The 90 and 80% confidence regions were estimated by using a red noise background spectrum. To reduce wraparound effects, each time series was padded with zeros.

3. Results

3.1. Skeletal Extension Rate

[15] Mean annual extension rate over the entire core is ~1.2 cm/yr, varying from ~0.8 cm/yr in 1790 to ~2.0 cm/yr in 1972 (Figure 3). During the late 18th to the middle 19th century the rate averages ~1.1 cm/yr (~215–266 cmbcs), which was followed by a gradual increase by ~0.3 cm from the 1860s to the 1960s (~62–182 cmbcs); then it rose abruptly to ~1.6 cm/yr for the last 30 years (~0–48 cmbcs). We assume that the kinetic disequilibrium is approximately constant in this Guam coral because skeletal formation

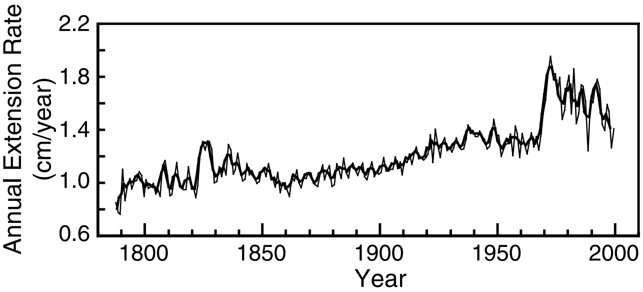

Figure 3. Annual skeletal extension rates in the Guam coral for the years 1787–2000. The bold line represents the variations smoothed with a 13-month moving average window.

exceeded ~0.5 cm/yr [*McConnaughey*, 1989; *Yamada*, 1998].

3.2. Coral Stable Isotopes

[16] We present monthly $\delta^{13}C_{coral}$ (carbon isotopic composition of a coral skeleton) and $\delta^{18}O_{coral}$ time series (Figure 4) for the years 1787–2000. The $\delta^{13}C_{coral}$ and $\delta^{18}O_{coral}$ profiles delineated from the overlapping portions of sample paths A and B (1944–1948) show coherent seasonal variations ($r \approx 0.84$ and 0.85 at $p < 0.01$, respectively). The stable isotope values are excessively high for the years 1787–1788 (Figures 4 and 5), consistent with the occurrences of marine cements at the lowermost part of the core (~270 to 273 cmbcs). Therefore we safely limit our consideration to the pristine sections of the core corresponding to the years 1790–2000.

[17] During the years 1790–2000 the $\delta^{13}C_{coral}$ values average −1.62‰ and display seasonal variations that average 1.14‰ but range from 0.44 to 2.76‰ (Figure 4a). The $\delta^{18}O_{coral}$ values average −5.01‰ and show seasonal variations that average 0.33‰ but range from 0.14 to 0.69‰ (Figure 4b). The $\delta^{18}O_{coral}$ time series smoothed with a 13-month moving average window contains interannual variations. Both $\delta^{13}C_{coral}$ and $\delta^{18}O_{coral}$ values tend to decrease from the early 19th century to the present.

4. Discussion

4.1. Carbon Isotopes

[18] Precise environmental interpretation of $\delta^{13}C_{coral}$ has remained elusive because many causes have been considered critical factors controlling the variations in $\delta^{13}C_{coral}$, including metabolic effects, kinetic effects linked with the rate of coral growth/calcification, and $\delta^{13}C$ of dissolved inorganic carbon in ambient seawater and incorporated organic food [e.g., *Weber and Woodhead*, 1970; *Nozaki et al.*, 1978; *Erez*, 1978; *Swart*, 1983; *McConnaughey*, 1989; *Swart et al.*, 1996]. The $\delta^{13}C_{coral}$ has been shown to be correlated with many environmental factors such as water depth [*Weber et al.*, 1976], light intensity [*Fairbanks and Dodge*, 1979], cloudiness [*Winter et al.*, 1991], atmospheric pressure [*Swart et al.*, 1996], and seawater pH [*Hemming et al.*, 1998].

[19] The monthly $\delta^{13}C_{coral}$ time series exhibits clear seasonal variations for the entire post-1820 portion of the record (Figure 4a). *Asami et al.* [2004] documented that there are weak but statistically significant correlations ($r \approx 0.56$ at approximately 1–2 month lag) between Guam

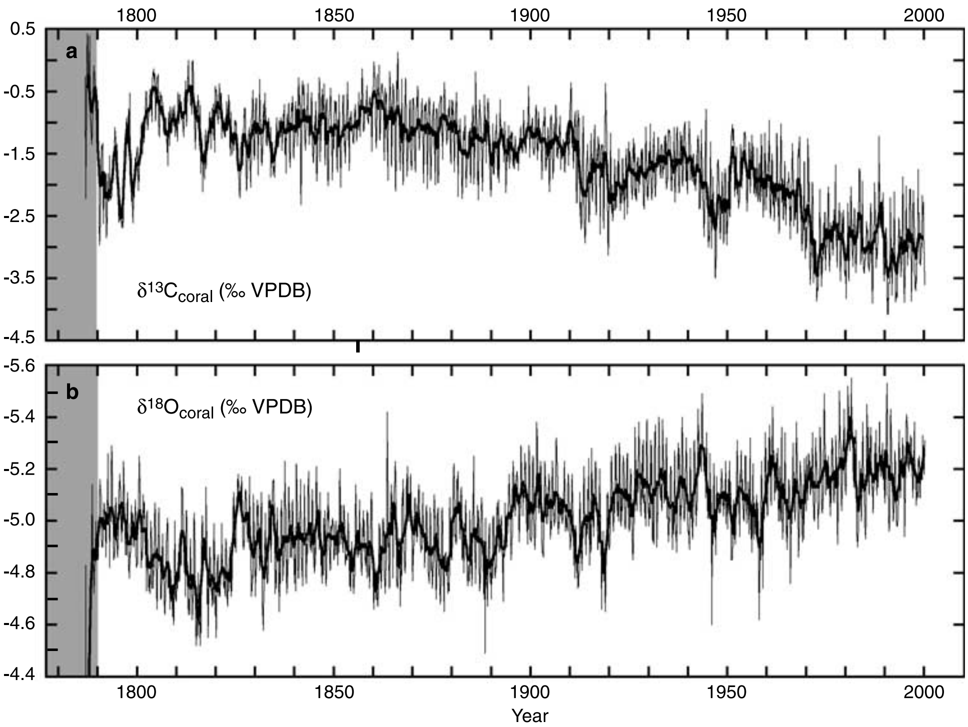

Figure 4. Monthly time series profiles of (a) carbon and (b) oxygen isotopes for the years 1787–2000. The bold line represents the variations in stable isotopes smoothed with a 13-month moving average window. Note that aragonitic marine cements are found in the lowermost part of the core (shaded area).

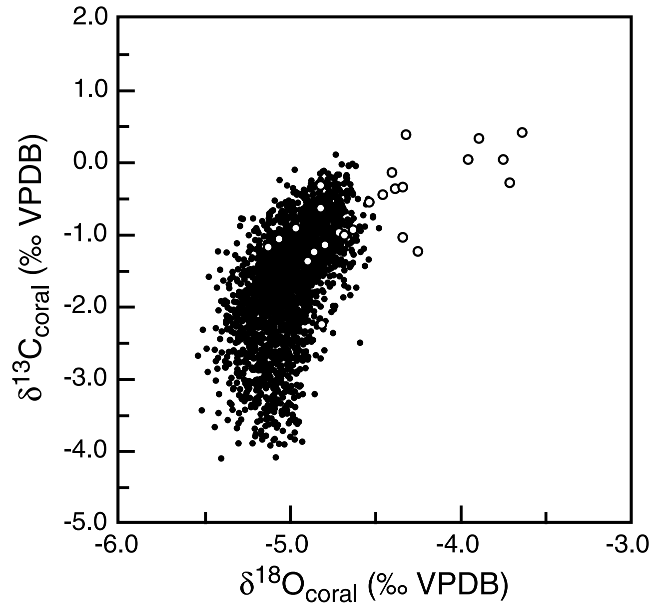

Figure 5. Scatterplot of monthly $\delta^{13}C_{coral}$ and $\delta^{18}O_{coral}$ values for the years 1789–2000 (solid circles) and the years 1787–1788 (open circles).

$\delta^{13}C_{coral}$ record and solar irradiance during the ENSO warm phases for the years 1980–2000. The only significant spectral peak in the $\delta^{13}C_{coral}$ time series is centered at 6.4 years, a periodicity that may be associated with ENSO variability. The long-term trend in the entire $\delta^{13}C_{coral}$ record (Figure 4a) shows a marked depletion in ^{13}C by ~2‰. In particular, there exists a remarkable depletion in ^{13}C by ~0.8‰ for the last 50 years, which corresponds to ~40% of the entire decrease in $\delta^{13}C_{coral}$. This result may reflect accelerated increase in the amount of anthropogenically derived CO_2 with low $\delta^{13}C$ values in the atmosphere for the latter half of 20th century. However, more observations are required to clarify the critical factors controlling the $\delta^{13}C_{coral}$ such as $\delta^{13}C$ of dissolved inorganic carbon of seawater.

4.2. Oxygen Isotopes

4.2.1. Comparison With Environmental Data

[20] Variations in $\delta^{18}O_{coral}$ are a function of changes in both SST and $\delta^{18}O_{sw}$, the latter of which is usually related to SSS. In regions where the $\delta^{18}O_{sw}$ is fairly constant and/or seasonal variations in SST are large, the $\delta^{18}O_{coral}$ has been used as a paleothermometer [e.g., *Dunbar et al.*, 1994; *Wellington et al.*, 1996; *Charles et al.*, 1997]. Conversely, in localities where there is little variation in SST the $\delta^{18}O_{coral}$ has been used to reconstruct SSS and $\delta^{18}O_{sw}$ variations, which are related to changes in the input of isotopically light rainfall [e.g., *Cole and Fairbanks*, 1990; *Linsley et al.*, 1994; *Urban et al.*, 2000]. *Asami et al.* [2004] demonstrated that the Guam $\delta^{18}O_{coral}$ records a composite signal of SST and SSS for the years 1980–2000. In this section, we compare the $\delta^{18}O_{coral}$ with SST for the years 1951–2000 (Hadl SST data) and SSS for the years 1969–1995 (ECOP SSS data).

[21] The $\delta^{18}O_{coral}$ and SST records show distinct seasonality and interannual variability with a significant cross correlation ($r = -0.67$, $n = 603$, and $p < 0.01$) for the last 50-year period (Figures 6a and 6b). The variations in $\delta^{18}O_{coral}$ smoothed with a 13-month moving average window after removing a long-term trend are well correlated with those in SST ($r = -0.53$ and $p < 0.01$). Cross-correlation coefficients of 0.43 and 0.49 are low but statistically significant at $p < 0.01$ and 0.05 between $\delta^{18}O_{coral}$ and SSS and between the two variables smoothed with a 13-month moving average window for the years 1969–1995 (Figures 6a and 6c), respectively. We calculated the anomaly of $\delta^{18}O_{coral}$, SST, and SSS by subtracting their monthly climatological means for the years 1950–1979 ($\delta^{18}O_{coral}$ and SST) and 1969–1995 (SSS). The $\delta^{18}O_{coral}$ anomaly is significantly correlated with SST anomaly (SSTA) ($r = -0.69$ and $p < 0.01$) and SSS anomaly (SSSA) ($r = 0.49$ and $p < 0.01$). These results suggest that changes in Guam $\delta^{18}O_{coral}$ are mainly influenced by SST and SSS variations on seasonal and interannual timescales. The 25-month (2-year window) moving correlation coefficient between monthly $\delta^{18}O_{coral}$ and SST varies from −0.90 to −0.19 (Figure 6d). The 2-year window moving correlation coefficient between monthly $\delta^{18}O_{coral}$ and SSS largely fluctuates from 0 to 0.80 (Figure 6d). Characteristically, the strong (weak) correlation between $\delta^{18}O_{coral}$ and SST generally coincides with the weak (strong) correlation between $\delta^{18}O_{coral}$ and SSS, for example, in 1972–1973, 1982–1983, and 1990–1991 (1975, 1985, and 1988), which corresponds well to ENSO warm phases (cool phases). Therefore this remarkable symmetry indicates that Guam $\delta^{18}O_{coral}$ is more (less) influenced by SST and is less (more) influenced by SSS during ENSO warm (cool) phases than during cool (warm) phases.

[22] We applied cross-spectral analysis at the 80% confidence level to identify the significant periodicity between monthly time series of the $\delta^{18}O_{coral}$ anomaly and SSTA for the years 1951–2000 and between the $\delta^{18}O_{coral}$ anomaly and SSSA for the years 1969–1995. The result of cross-spectral analysis (Figure 7a) reveals significant coherence with the 180° out-of-phase relation between monthly $\delta^{18}O_{coral}$ anomaly and SSTA at 2.5, 3.6, and 9.3 years. Cross-spectral analysis between monthly $\delta^{18}O_{coral}$ anomaly and SSSA (Figure 7b) shows significant coherence at 5.6 years. The occurrence of spectral peaks at 3.6 and 5.6 years is consistent with a coral $\delta^{18}O$ response to ENSO forcing because the ENSO event frequency band is ~3–8 years [e.g., *Rasmusson et al.*, 1990]. The ENSO periodicity of 3.6 years is also found in a cross-spectral analysis between $\delta^{18}O_{coral}$ anomaly and SSTA in the Niño 3.4 region (5°S–5°N, 120°–170°W) (Figure 7c), the latter of which is derived from Climate and Global Dynamics Division of National Center for Atmospheric Research. The SST (SSS) variability explains 77% (69%) of the $\delta^{18}O_{coral}$ variance at the ENSO cycle. These results suggest that Guam $\delta^{18}O_{coral}$ is influenced significantly by SST and SSS variability relating to ENSO warm and cool phases.

4.2.2. Interannual Variability

4.2.2.1. ENSO Reconstruction

[23] The WPWP is a source area for a substantial proportion of the Earth's interannual climate variability, including the global ENSO events [*McPhaden and Picaut*, 1990; *Webster and Lukas*, 1992], because the WPWP has the warmest SST of >28°C and is one of those regions where a

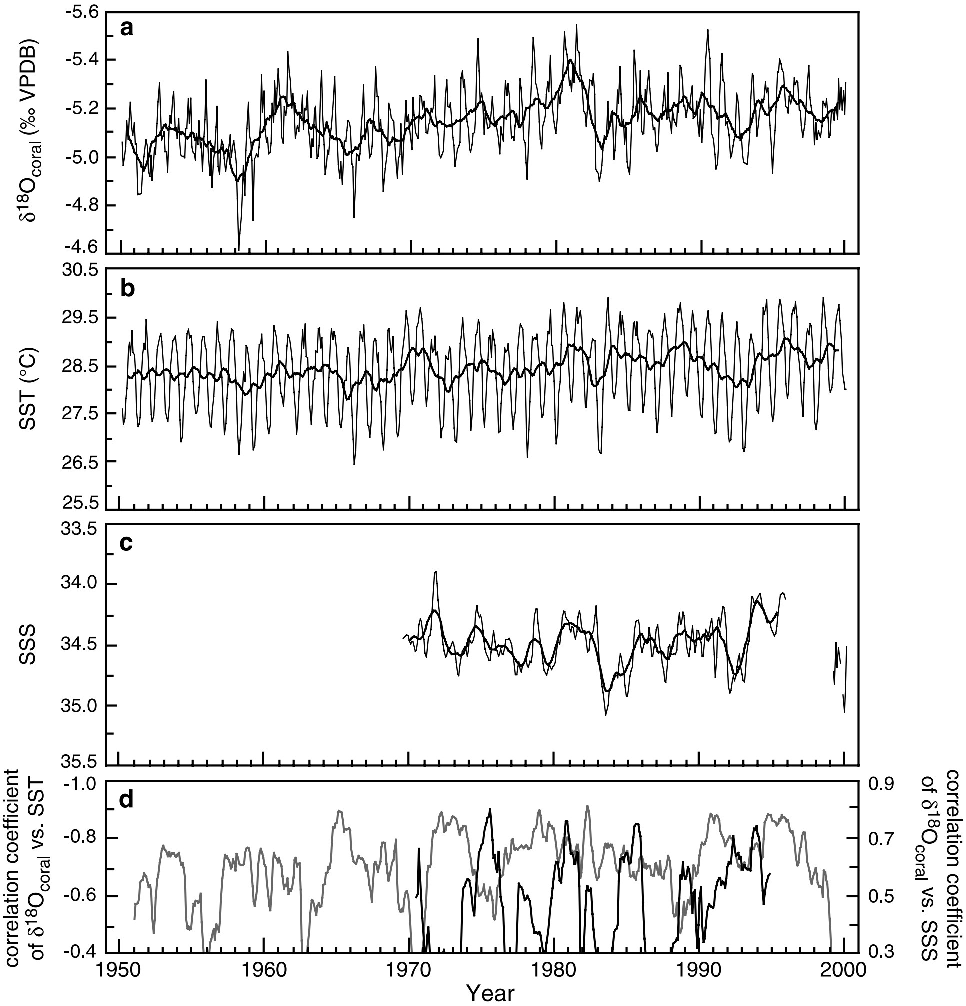

Figure 6. Monthly variations in (a) $\delta^{18}O_{coral}$, (b) Hadl SST, and (c) Etudes Climatiques de l'Ocèan Pacifique tropical sea surface salinity (SSS) for the years 1950–2000. The bold lines show the variations smoothed with a 13-month moving average window. The SSS data for the years 1999–2000 are derived from *Asami et al.* [2004]. (d) Moving correlation coefficients of 2-year window between $\delta^{18}O_{coral}$ and SST (shaded line) and between $\delta^{18}O_{coral}$ and SSS (solid line).

large amount of latent heat release occurs associated with precipitation. There are many references reporting that $\delta^{18}O_{coral}$ is an excellent archive of ENSO activity because ENSO accompanies pronounced SST fluctuations in the eastern and central equatorial Pacific [e.g., *Cole et al.*, 1993; *Dunbar et al.*, 1994] and enhanced precipitation in the south western Pacific [e.g., *Tudhope et al.*, 1995; *Le Bec et al.*, 2000]. Surface waters around Guam experience thermal and hydrologic changes caused by eastward (westward) migration of the WPWP during ENSO warm (cool) phases because the island lies in the northern edge of the WPWP during non-ENSO phases (Figure 1). *Asami et al.* [2004] demonstrated that an ENSO warm phase resulted in a positive $\delta^{18}O_{coral}$ anomaly because of lower SST caused by eastward migration and expansion of the WPWP. In contrast, an ENSO cool phase resulted in a negative $\delta^{18}O_{coral}$ anomaly because of higher winter SST caused by westward migration of the WPWP.

[24] After removing long-term trend and decadal variability of $\delta^{18}O_{coral}$ we calculated the monthly $\delta^{18}O_{coral}$ anomaly for the years 1790–2000 (Figure 8a) relative to monthly average values for the years 1950–1979, a base period of climatology, in order to compare with Niño 3.4 SSTA (Figure 8b). The Niño 3.4 SSTA is considered an excellent indicator of ENSO variability [*Trenberth*, 1997; *Trenberth and Stepaniak*, 2001]. Positive (negative) anomaly in Guam $\delta^{18}O_{coral}$ coincides well with positive (negative) anomaly in Niño 3.4 SST for ENSO warm (cool) phases. ENSO events are defined in this study when the 5-month running mean of $\delta^{18}O_{coral}$ anomaly exceeds ~0.04‰, corresponding to SSTA by ~0.3°C, for 5 consecutive months or more. When this definition was applied to the $\delta^{18}O_{coral}$ record, 46 ENSO warm and 53 cool phases were detected for the years 1790–2000. Large excursions in the $\delta^{18}O_{coral}$ anomaly record prior to 1870 imply that strong ENSO warm and cool phases occurred 7 times (1808–1809, 1814–1816, 1822–1823, 1831–1832, 1854–1855, 1860–1861, and 1866–1867) and 8 times (1800–1801, 1810–1812, 1816–1817, 1825–1826, 1833–1834, 1845–1846, 1864–1865, and 1868–1869), respectively. Sixty-two percent of the ENSO

warm phases derived from Niño 3.4 SSTA for the years 1870–2000 are recognized in our reconstruction. Our reconstruction identifies ~79% of the strong ENSO warm phases indicated by 5-month running means of Niño 3.4 SSTA of >1°C. The ENSO cool phases recorded in the $\delta^{18}O_{coral}$ anomaly coincide with ~44% of cool phases found in Niño 3.4 SSTA and ~62% of strong cool phases indicated by the excess by less than −1°C. The high correspondence of ENSO warm phases between the two records is attributed to the fact that positive $\delta^{18}O_{coral}$ anomaly is clearly recorded because of a combined effect of lower SST and higher $\delta^{18}O_{sw}$ for ENSO warm phases. In contrast, surface water in Guam for ENSO cool phases is characterized by higher SST and is accompanied typically by higher $\delta^{18}O_{sw}$ anomaly due to enhanced evaporation in summer [*Asami et al.*, 2004], which results in indistinct and/or intermittent negative $\delta^{18}O_{coral}$ anomaly and consequently the weak correspondence of the coral record with ENSO cool phases found in Niño 3.4 SSTA record. Some ENSO warm phases (e.g., 1884, 1936–1937, and 1946–1947) and cool phases (e.g., 1897–1998, 1901–1902, 1921–1922, and 1961–1962) detected in Guam coral data are not found in the Niño 3.4 SSTA but moderate SSTA occurred in Niño 3.4 region for such ENSO events. We consider that these ENSO events may be inconspicuous because weakening (strengthening) of westward wind was not remarkable, resulting in incomplete eastward (westward) migration of the WPWP for ENSO warm phases (cool phases). Such incomplete behavior of the WPWP can be deciphered from spatial patterns of SSTA [e.g., *Allan et al.*, 1996]. Furthermore, a strong warm phase of ENSO in 1972–1973 and cool phases in 1889–1890 and 1973–1974 are not identified in our reconstruction. Such disagreement of ENSO reconstructions by Niño 3.4 SSTA and our study is possibly attributed to the fact that (1) mode and degree of climatic anomaly caused by ENSO events vary from place to place and (2) Guam $\delta^{18}O_{coral}$ reflects not only SST but also SSS variations. However, the time series of Guam $\delta^{18}O_{coral}$ anomaly significantly shows thermal and hydrologic changes in the northwestern tropical Pacific relating to past ENSO events for the last 210 years.

[25] On the basis of the Guam $\delta^{18}O_{coral}$ record the early 19th century (1801–1820) was the coolest in the past 210 years, which is consistent with SST reconstructions from a $\delta^{18}O_{coral}$ record from New Caledonia [*Crowley et al.*, 1997]. The early 19th century was characterized by a

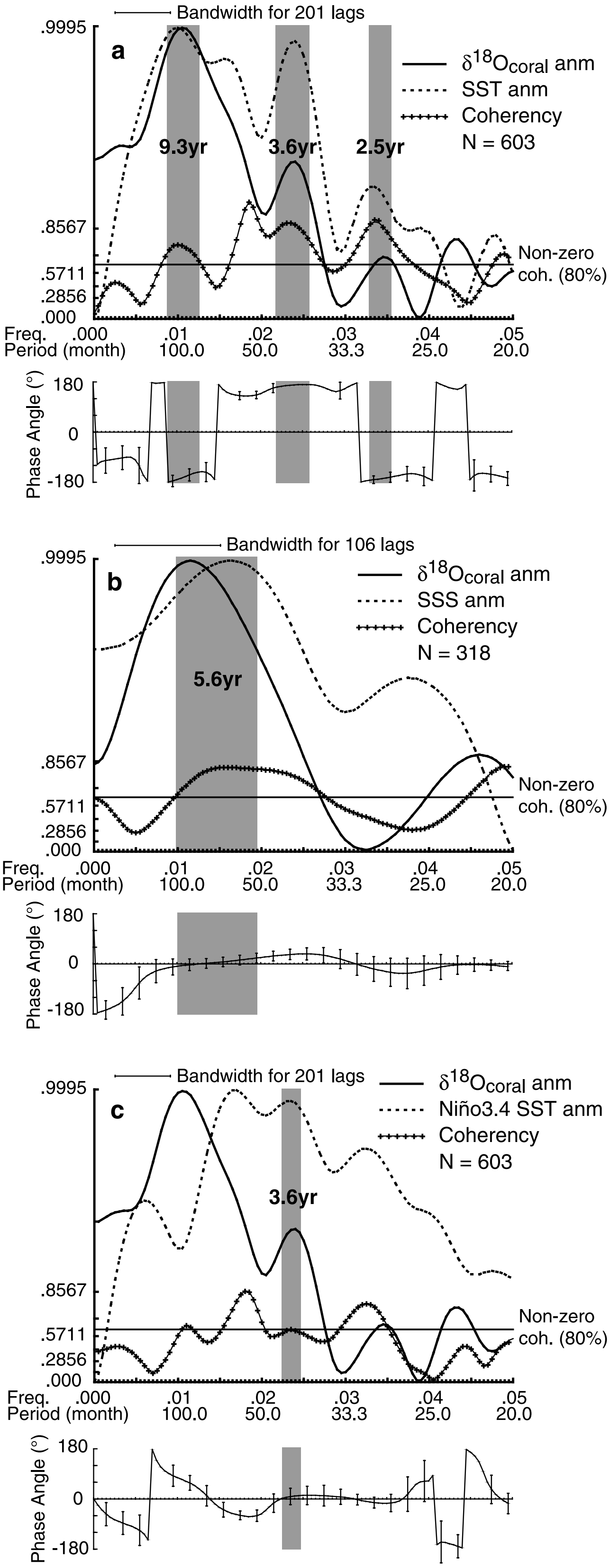

Figure 7. Cross-spectral plots (a) between monthly $\delta^{18}O_{coral}$ anomaly and SST anomaly (SSTA) for the years 1950–2000, (b) between monthly $\delta^{18}O_{coral}$ anomaly and SSS anomaly (SSSA) for the years 1969–1995, and (c) between monthly $\delta^{18}O_{coral}$ anomaly and Niño 3.4 SSTA for the years 1950–2000. The topmost plot in each panel shows the variance spectra plotted as the normalized log of the spectral density. The spectral density equals variance divided by frequency of the $\delta^{18}O_{coral}$ anomaly (solid line) and that of the SSTA, SSSA, or Niño 3.4 SSTA (dashed line). Coherency, the correlation coefficient as a function of frequency, is shown as a solid line with pluses. The 80% confidence bandwidth for the variance spectra are given in the top left of each panel. The 80% coherency significance level is shown as the horizontal line. The bottommost plot in each panel illustrates the phase relationship between the two time series. For cross-spectral analyses in this study we used a linear detrend of the entire raw data and no prewhitening.

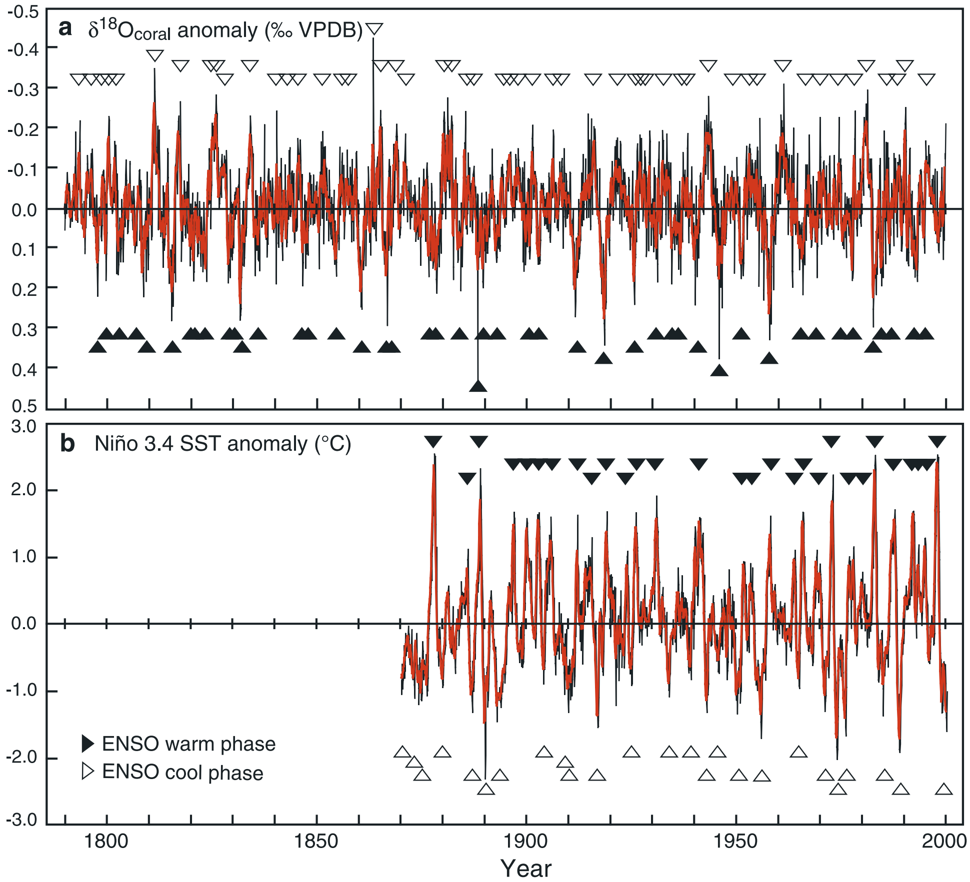

Figure 8. Monthly time series of (a) $\delta^{18}O_{coral}$ anomaly for the years 1790–2000 and of (b) Niño 3.4 SSTA for the years 1870–2000, which are relative to monthly mean values for the years 1950–1979, a base period of climatology. The red lines represent the 5-month running mean time series. ENSO warm (solid triangles) and cool (open triangles) phases are also shown.

decrease in solar irradiance [*Lean et al.*, 1995; *Crowley and Kim*, 1996] and by a series of large volcanic eruptions in 1808–1809 and 1812–1822 [*Crowley et al.*, 1997]. Several excursions toward cool conditions are recognized in the $\delta^{18}O_{coral}$ record (Figure 4b) in the years 1831–1832, 1882–1883, 1917–1918, 1963–1964, and 1991–1992. These excursions correspond to the eruptions in the regions of the western Pacific in 1831 (Babuyan, Philippines), 1883 (Krakatau, Indonesia), 1917 (Agrigan, Mariana), 1963 (Agung, Indonesia), and 1991 (Pinatubo, Philippines), respectively. However, it is difficult to separate a volcanic signal from ENSO warm phase–induced cooling. Quantitative interpretations of volcanic eruptions in coral records would require more verification in further investigations.

4.2.2.2. ENSO Frequency

[26] The MTM analysis of the monthly anomaly time series of the Guam $\delta^{18}O_{coral}$ record for the 210 years reveals the concentration of its variance in the period of 5.7–5.9 years, which exceeds the 90% confidence level (Figure 9). This interannual peak indicates a response of $\delta^{18}O_{coral}$ to the ENSO forcing. Several peaks of 2.8–2.9, 3.4, 3.7, 5.4, and 6.6 years, although they are not significant at the 90% confidence level, can be identified by the MTM analysis, which may also reflect the interannual variability associated with ENSO cycles. Concentrations of variance in the ENSO frequency band (3–8 years) have also been identified in long $\delta^{18}O_{coral}$ records from the equatorial Pacific Ocean [e.g., *Dunbar et al.*, 1994; *Quinn et al.*, 1993; *Cobb et al.*, 2001]. In the western Pacific, $\delta^{18}O_{coral}$ records display significant variability with 3- to 5-year periodicity in Papua New Guinea [*Tudhope et al.*, 1995] and with 3.5- and 5.5-year periodicity in Indonesia [*Charles et al.*, 2003]. The ~3.6-year peak also has been detected from analysis of climatic variables such as the Southern Oscillation index [*Allen and Smith*, 1996; *Brassington*, 1997] and temperature and sea level pressure records in the Northern Hemisphere [*Mann and Park*, 1994]. The ~3.6-year periodicity is recognized in the $\delta^{18}O_{coral}$ and SST variations around Guam for the last 50 years as well.

[27] To highlight the changes in the interannual periodicity in the time domain, we performed wavelet analysis of the 5-month running mean time series of the $\delta^{18}O_{coral}$ anomaly for the years 1790–2000 (Figure 10a). The wavelet power spectra of Niño 3.4 SSTA (Figure 10b) show significant variability with relatively shorter periodicity of ~2–4 years for ~1870–1910, ~4–8 years for ~1910–1960, and ~2–6 years for ~1960–2000, which suggests that ENSO frequency is not constant but variable. The $\delta^{18}O_{coral}$ record has significant variance with periodicity of ~4–8 years roughly for the entire period, occasionally accompanying relatively shorter periodicity of 2–4 years, which are punctuated by indistinct concentration of variance

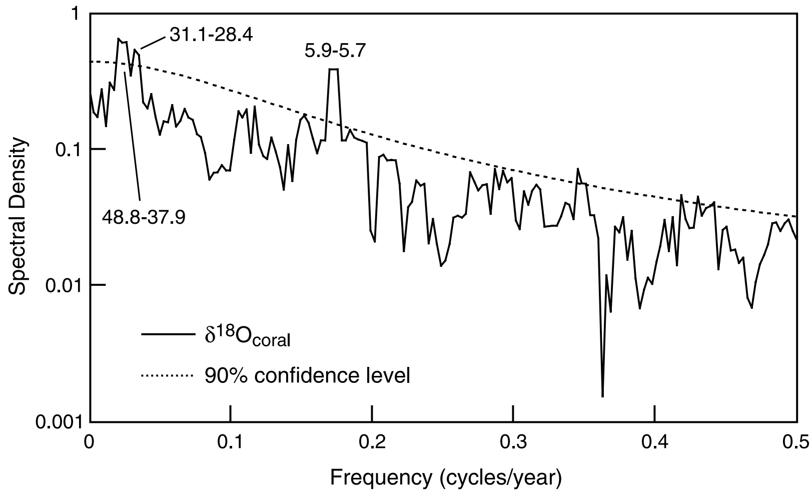

Figure 9. Frequency domain analysis of monthly $\delta^{18}O_{coral}$ anomaly for the years 1790–2000 as produced by the multitaper method. The 90% confidence level is shown as the dashed line. The numbers denote the interannual to decadal periodicity with significant peaks at 90% confidence level.

(Figure 10a). This result indicates that around Guam, interannual variability of sea surface condition associated with ENSO events is variable in magnitude and frequency. Difference of variance between Guam $\delta^{18}O_{coral}$ and Niño 3.4 SSTA may be attributed to that the $\delta^{18}O_{coral}$ reflects SSS as well as SST and/or that the magnitude of SSTA associated with ENSO activity varies from place to place and is larger in the Niño 3.4 and Niño 3 (5°S–5°N, 90°–150°W) regions than it is in the western Pacific.

[28] The $\delta^{18}O_{coral}$ record has concentration of variance, although it is not so distinct, with the periodicity of <4 years for the years 1950–2000, which is consistent with the significant periodicity of 3.6 years (Figure 7a) and with increased occurrences of ENSO warm and cool phases for the last 50 years (Figure 8). *Tudhope et al.* [1995] documented that a $\delta^{18}O_{coral}$ record from the western equatorial Pacific indicates a marked change in dominant periodicity from a rather diffuse concentration of variance at a >5-year period, prior to the late 1950s, to an increased concentration of variance within a 3- to 5-year period after that time. Both Tarawa [*Cole et al.*, 1993] and Clipperton [*Linsley et al.*, 2000] coral $\delta^{18}O_{coral}$ records show increased ENSO band variability since ~1950. However, relatively less distinct concentration of variance with a cyclicity of <4 years in Guam $\delta^{18}O_{coral}$ record likely reflects the less distinct climatic signals of ENSO events around Guam relative to other equatorial Pacific regions and the characteristic signals of the $\delta^{18}O_{coral}$ relating to both SST and $\delta^{18}O_{sw}$. The latter may explain some differences in the variance patterns of $\delta^{18}O_{coral}$ (Figure 10a) and SST (Figure 10c).

[29] Diminished excursions of $\delta^{18}O_{coral}$ anomaly are found in the 1790s–1800s, 1830s–1850s, and 1890s–1910s (Figure 8a), which correspond roughly to decreased concentration of variance in the results of the wavelet analysis. Excursions of $\delta^{18}O_{coral}$ anomaly are also diminished from the 1920s to the 1940s, which may be related to the weakening of the Southern Oscillation from the 1920s to 1940s [*Trenberth and Shea*, 1987; *Allan et al.*, 1996]. Although the wavelet power spectra show slightly decreased concentrations of variance of ENSO periodicity for this period, the cause cannot be specified at this time.

4.2.3. Decadal Variability

[30] The Guam $\delta^{18}O_{coral}$ time series displays low-frequency fluctuations with relatively small amplitude of ~0.1–0.2‰ with periods ranging from a decade to several decades (Figure 4b). The MTM analysis of the $\delta^{18}O_{coral}$ reveals significant periodicity of ~28.4–31.1 and ~37.9–48.8 years for the years 1790–2000 (Figure 9). The wavelet power spectrum of the monthly $\delta^{18}O_{coral}$ anomaly for the entire period shows the most significant variability with ~20- to 40-year periodicity for the years 1870–1940 and relatively significant variability with ~15-year periodicity for the years 1810–1830 and 1860–1900 (Figure 11). Visual inspection of the $\delta^{18}O_{coral}$ profile confirms that relatively warmer and wetter periods represented by lower $\delta^{18}O_{coral}$ values alternate with relatively cooler and drier periods indicated by higher $\delta^{18}O_{coral}$ values. For example, the former includes 1790 to the early 1800s and the mid-1890s to the late 1910s, and the latter includes the early 1800s to the mid-1820s and the mid-1940s to the late 1960s.

[31] To evaluate whether the transition from a particular warm (cool) state to the subsequent cool (warm) state is significant or not, we calculated the time series of difference between the average of two adjacent 10-year periods from the yearly $\delta^{18}O_{coral}$ values. Then, we suppose that the abrupt transition is regarded as the significant difference at the 95% confidence level based on the t statistic (Figure 12). The significant abrupt shifts detected by our estimation occurred at 1800–1801, 1823–1824, 1852–1853, 1862–1863, 1893–1894, 1909–1910, 1920–1921, 1945–1946, 1958–1959, and 1972–1973. The amplitude of these $\delta^{18}O_{coral}$ transitions varies from ~0.07‰ in 1945–1946 and 1958–1959 to ~0.19‰ in 1893–1894. For the 20th century the anomaly of $\delta^{18}O_{coral}$ variations is correlated with that of SST variations given by *Kaplan et al.* [1998] (available at http://iridl.ldeo.columbia.edu/SOURCES/.KAPLAN/.RSA_MOHSST5.cuf/), with significant cross-correlation coefficient of −0.59 at $p < 0.01$. The anomaly of Kaplan

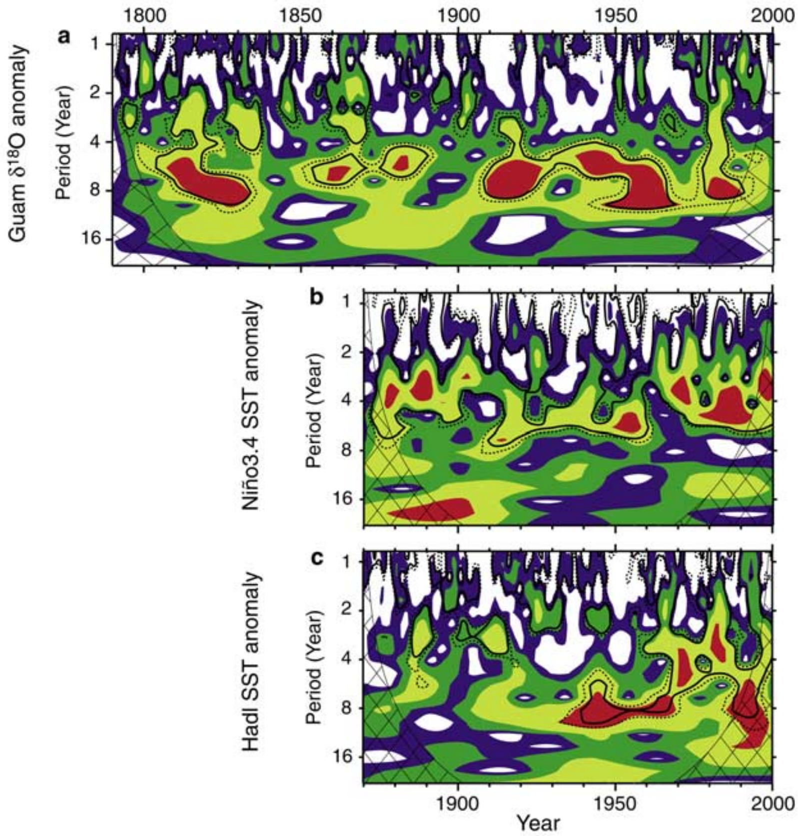

Figure 10. Wavelet power spectrum using the Morlet wavelet of the 5-month running mean time series of (a) $\delta^{18}O_{coral}$ anomaly for the years 1790–2000 (Figure 8a), (b) Niño 3.4 SSTA for the years 1870–2000 (Figure 8b), and (c) Hadl SSTA for the years 1870–2000. The contour levels are chosen so that 75% (red), 50% (yellow), 25% (green), and 5% (blue) of the wavelet power is above each level, respectively. The solid and dashed black contours enclose regions of >90 and >80% confidence for a red noise, respectively. Cross-hatched regions on either end indicate the "cone of influence," where edge effects become important.

SST indicates a warming (or cooling) of ~0.3°C around Guam at each $\delta^{18}O_{coral}$ transition. On the basis of the slope of the equation established by *Asami et al.* [2004] this warming (or cooling) is equivalent to a decrease (or increase) in $\delta^{18}O_{coral}$ of ~0.05‰, which indicates that the transitions of Guam $\delta^{18}O_{coral}$ are not attributed only to the SST transitions. Thus the $\delta^{18}O_{coral}$ record suggests a depletion (or increase) in $\delta^{18}O_{sw}$ of less than ~0.13‰, corresponding to the additional decrease (or increase) in salinity of less than ~0.48, at each transition.

[32] Decadal variability in the North Pacific has been actively discussed in recent years [e.g., *Graham*, 1994; *Mann and Park*, 1996; *Nakamura and Yamagata*, 1999]. *Mantua et al.* [1997] defined the Pacific Decadal Oscillation (PDO) persisting for approximately 20–30 years, which is also referred as the North Pacific Interdecadal Oscillation [*Gershunov et al.*, 1999]. The PDO is defined as the leading empirical orthogonal function of the North Pacific SST that accounts for the largest fraction of the spatially integrated variance. During warm (cool) PDO phases, SST tends to be lower (higher) in the central North Pacific in contrast to higher (lower) SST along the west coast of the Americas and in the eastern equatorial Pacific. The climate regime shifts identified by some authors [e.g., *Ebbesmeyer et al.*,

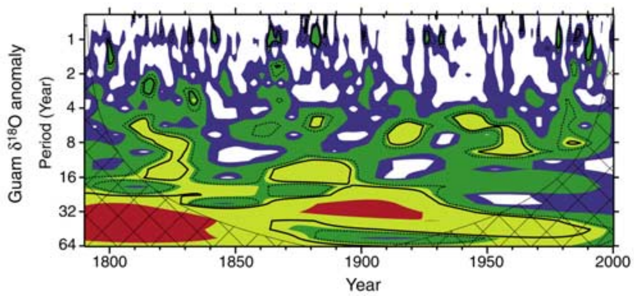

Figure 11. Wavelet power spectrum using the Morlet wavelet of the monthly $\delta^{18}O_{coral}$ anomaly for the years 1790–2000 after removing a linear long-term trend. The contour levels are chosen so that 75% (red), 50% (yellow), 25% (green), and 5% (blue) of the wavelet power is above each level, respectively. The solid and dashed black contours enclose regions of >90 and >80% confidence for a red noise, respectively. Cross-hatched regions on either end indicate the "cone of influence," where edge effects become important.

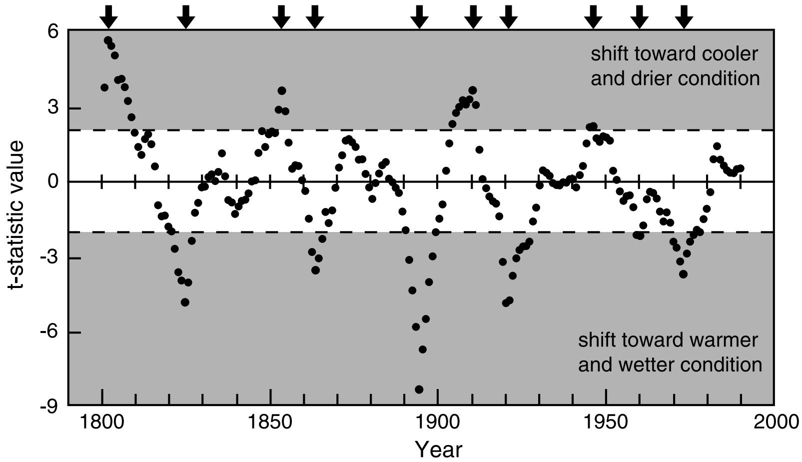

Figure 12. The *t* statistic test of difference between the two average values of the adjacent 10 years for the last 2 centuries. Horizontal dashed lines show the significance at the 95% confidence level (±2.101). Arrows indicate occurrences of the significant transitions toward cooler and drier and/or toward warmer and wetter conditions.

1991; *Minobe*, 2000; *Yasunaka and Hanawa*, 2002, 2003] correspond with the decadal-scale oceanographic and climatic changes in the North Pacific and generally coincide with the transition from positive (negative) to negative (positive) phases of the PDO index.

[33] The Guam $\delta^{18}O_{coral}$ time series for the 20th century show decadal variability correlative with the PDO index ($r = -0.52$ at ~2 years lag) of *Mantua et al.* [1997]. The MTM and wavelet analyses showed the significant decadal variability of ~15 to ~45 year periodicity in the $\delta^{18}O_{coral}$ record (Figures 9 and 11). Concentrations of variance at these periods correspond possibly to one of the most energetic fluctuations of North Pacific sea surface conditions. It is, however, inferred that the mechanism generating the decadal variability of the oceanographic conditions around Guam is highly complicated because the wavelet periods change greatly through the years 1790–2000. The significant shift in 1945–1946 found in the $\delta^{18}O_{coral}$ record (Figure 12) is consistent with the 1945–1946 regime shift indicated by many workers [e.g., *Yasunaka and Hanawa*, 2002]. The $\delta^{18}O_{coral}$ shifts in 1920–1921 and 1972–1973 recovered in this study (Figure 12) precede the regime shifts (1925–1926 and 1976–1977) by a few years. *Yasunaka and Hanawa* [2002, 2003] detected the regime shifts in the winter SST field in the Northern Hemisphere from the 1910s to the 1990s: the 1925–1926, 1945–1946, 1957–1958, 1970–1971, 1976–1977, and 1988–1989 regime shifts. However, these SST shifts are inconspicuous in the tropical western Pacific. *Mantua et al.* [1997] stated that the primary climatic effects of the PDO are concentrated in the North Pacific with secondary signatures in the tropics, whereas ENSO events dominate the equatorial Pacific and have secondary effects in other parts of the Pacific. Nevertheless, the results of spectral analyses and detection of significant shifts in this study suggest that Guam $\delta^{18}O_{coral}$ has primarily responded to not only interannual forcing but also decadal forcing in the western Pacific since 1790.

4.2.4. Long-Term Trend

[34] The long-term $\delta^{18}O_{coral}$ trend is characterized by its overall depletion throughout the period (Figure 4b), indicative of an overall trend toward warmer and wetter conditions. There were, however, several intermittent periods with the opposite tendency, including the one in the early 1800s that has already been identified in coral records and temperature variations in the Northern Hemisphere [e.g., *Bradley and Jones*, 1993; *Crowley et al.*, 1997].

[35] We estimate a 0.35‰ decrease for 2 centuries in annual $\delta^{18}O_{coral}$ over the entire record, assuming that the $\delta^{18}O_{coral}$ record nearly shows a linear trend estimated on the basis of least squares fitting ($r = -0.76$ and $p < 0.01$). The depletion of annual $\delta^{18}O_{coral}$ is 0.18‰ for the 20th century, which is ~0.12‰ greater than the theoretical decrease in $\delta^{18}O_{coral}$ value calculated from SST warming by ~0.39°C observed in Hadl SST series. This suggests a decrease in $\delta^{18}O_{sw}$ by ~0.12‰ which is equivalent to a decrease in SSS by ~0.44 using the equation of *Fairbanks et al.* [1997]. The gradual decrease in $\delta^{18}O_{coral}$ by 0.17‰ from 1790 to 1899 would have corresponded to ~0.36°C warming of SST and ~0.11‰ freshening of $\delta^{18}O_{sw}$ if we had extrapolated the relation between SST increase and $\delta^{18}O_{sw}$ decrease for the 20th century to the full coral record. A cumulative decrease of 0.35‰ in Guam $\delta^{18}O_{coral}$, reflecting a combination of warming (~0.75°C) and freshening of the surface waters (~0.23‰), implies an expansion of WPWP over the last 2 centuries because Guam lies at the northern edge of the WPWP at the present. A coral $\delta^{18}O$ from Maiana Atoll at the eastern edge of the present warm pool also shows a trend toward warming and freshening of seawater over the past 155 years [*Urban et al.*, 2000], which may support our inference. More reliable interpretation of long-term $\delta^{18}O_{coral}$ trend requires careful consideration of other possible nonclimatic factors, including a potential biologically mediated shift in the vital effect (e.g., change in depth of colony surface) or other unknown coral growth effects.

5. Conclusions

[36] 1. A monthly resolved, 210-year (1790–2000) time series of stable isotopic variations in a coral from Guam (13°N, 145°E), which is located at the northern edge of the

western Pacific warm pool, shows seasonal, interannual, and decadal variability consistent with significant oceanographic changes related to thermal and hydrologic variations around Guam.

[37] 2. The monthly $\delta^{13}C_{coral}$ time series show clear seasonal variations for the post-1820s portion of the record. The long-term trend in the entire record of $\delta^{13}C_{coral}$ shows a marked depletion in ^{13}C by ~2‰. In particular, there exists a distinct depletion in ^{13}C by ~0.8‰ for the last 50 years. It is highly probable that $\delta^{13}C$ of the Guam coral is influenced by many factors such as solar irradiance and $\delta^{13}C$ of dissolved inorganic carbon in ambient seawater.

[38] 3. A comparison of monthly $\delta^{18}O_{coral}$ with SST for the years 1951–2000 shows distinct seasonal and interannual variability with a significant cross correlation ($r = -0.67$ and $p < 0.01$). Cross-correlation coefficient ($r = 0.43$) is low but statistically significant ($p < 0.01$) between $\delta^{18}O_{coral}$ and SSS for the years 1969–1995. The 13-month smoothed variations in $\delta^{18}O_{coral}$ anomaly are correlated with those in SSTA ($r = -0.69$) and SSSA ($r = 0.49$). These results suggest that Guam $\delta^{18}O_{coral}$ reflects SST and SSS variations on seasonal and interannual timescales. The 2-year moving correlation coefficients between $\delta^{18}O_{coral}$ and SST and between $\delta^{18}O_{coral}$ and SSS show that the strong (weak) correlations in the former coincide well with the weak (strong) correlations in the latter, which corresponds highly to ENSO warm phases (cool phases).

[39] 4. The cross-spectral analysis reveals significant inverse coherence between $\delta^{18}O_{coral}$ anomaly and SSTA at ~3.6 years and significant coherence between $\delta^{18}O_{coral}$ anomaly and SSSA at ~5.6 years, which is consistent with ENSO forcing. We detected 46 ENSO warm and 53 cool phases from the entire record of this coral, which correlate well with those reconstructed using the SSTA record from the Niño 3.4 region.

[40] 5. The MTM analysis of the monthly $\delta^{18}O_{coral}$ anomaly for the years 1790–1999 identifies ENSO periodicity with significant peaks at ~5.8 years and some peaks around ~3 to ~7 years. The wavelet power spectra show that the $\delta^{18}O_{coral}$ record commonly has significant variance with periodicity of ~4–8 years for the entire period, with occasional intervals with relatively shorter periodicity and others with indistinct concentrations of variance. These results indicate that the Guam $\delta^{18}O_{coral}$ contains a record of global ENSO forcing over the last 2 centuries.

[41] 6. The MTM and wavelet analyses of monthly $\delta^{18}O_{coral}$ anomaly reveals decadal variability varying from ~15- to ~45-year periodicity with significant shifts (<0.2‰) from warmer to cooler conditions and vice versa. The decadal variability is consistent with several significant transitions detected in this study. Consequently, Guam $\delta^{18}O_{coral}$ may reflect a decadal-scale variability in the North Pacific relating possibly to PDO and/or other climate regime shifts.

[42] 7. The long-term $\delta^{18}O_{coral}$ trend is characterized by isotopic depletion toward the present. An accumulative decrease of the entire record (1790–2000) may correspond to ~0.75°C warming of SST and ~0.23‰ decrease of $\delta^{18}O_{sw}$, corresponding to increase in salinity of ~0.85, in Guam for the last 2 centuries, which may imply an expansion of WPWP over that period.

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