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El Niño Southern Oscillation (ENSO) and decadal-scale climate variability at 10°N in the eastern Pacific from 1893 to 1994: A coral-based reconstruction from Clipperton Atoll

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Abstract: We have developed a 101 year (1893-1994) subseasonal oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopic time series from Clipperton Atoll in the eastern Pacific using the coral *Porites lobata*. In agreement with *Linsley et al.* [1999] we find that seasonal and interannual coral $\delta^{18}O$ variability at Clipperton results from variability in both water temperature and salinity. Three new coral time series demonstrate the reproducibility of a secular coral $\delta^{18}O$ trend of -0.35‰ since 1910 but show varying $\delta^{13}C$ trends. Strong decadal-scale variability in the $\delta^{18}O$ record appears related to the Pacific Decadal Oscillation (PDO) through postulated changes in the strengths of the Equatorial Counter Current and North Equatorial Current. Interannual variability in this coral $\delta^{18}O$ record is directly related to the El Niño Southern Oscillation (ENSO) and isolation of this frequency band indicates reduced ENSO variability in the eastern equatorial Pacific in the period 1925 to ~1940, in agreement with instrumental and other Pacific coral records.

1. Introduction

Interannual, decadal, and secular changes in Pacific surface oceanographic conditions remain poorly constrained before ~1950 because of sparse temporal and spatial instrumental data coverage. Of these time scales of variability, interannual changes related to the El Niño Southern Oscillation (ENSO) system are the most well understood. There is growing evidence that ENSO may contribute and/or respond to decadal-scale variability [*Jacobs et al.*, 1994; *Trenberth and Hurrell*, 1994; *Gu and Philander*, 1997; *Zhang et al.*, 1997; *Guilderson and Schrag*, 1998; *Zhang et al.*, 1998] and that the decadal-scale changes in ENSO may at least partly originate in the subtropics [*Gu and Philander*, 1997; *Guilderson and Schrag*, 1998; *Zhang et al.*, 1998]. Periods of both weaker and stronger Southern Oscillation (SO) were first noted by *Schell* [1956] and *Berlage* [1961, 1966], and more recent studies have identified a long-term shift in the ENSO system beginning in 1976 [*Graham*, 1994; *Gu and Philander*, 1997; *Latif and Barnett*, 1994a,b; *Trenberth and Hurrell*, 1994]. With the advent of possible anthropogenic warming, additional changes in the strength and pacing of ENSO could result. Whether we are already witnessing signs of an anthropogenic effect on ENSO is currently being debated. *Trenberth and Hoar* [1996] and *Harrison and Larkin* [1997] provide opposing statistical arguments about the extent to which the 1990-1995 ENSO is an unusual or unique event. Another unexplained example of decadal-scale change in ENSO behavior occurred from 1925 to 1945. This period was a time of weak ENSO indices and reduced coupling between the eastern and western Pacific [*Trenberth and Shea*, 1987; *Elliott and Angell*, 1988; *Cooper and Whysall*, 1989; *Pan and Oort*, 1990; *Enfield and Cid*, 1991; *Allan*, 1993; *Allan et al*, 1996]. Understanding the cause(s) and recurrence interval of these "regime" shifts in ENSO and their relationship to decadal and secular oceanographic changes will require the development of a spatial array of annually resolved paleoclimatic records that extend back >100 years.

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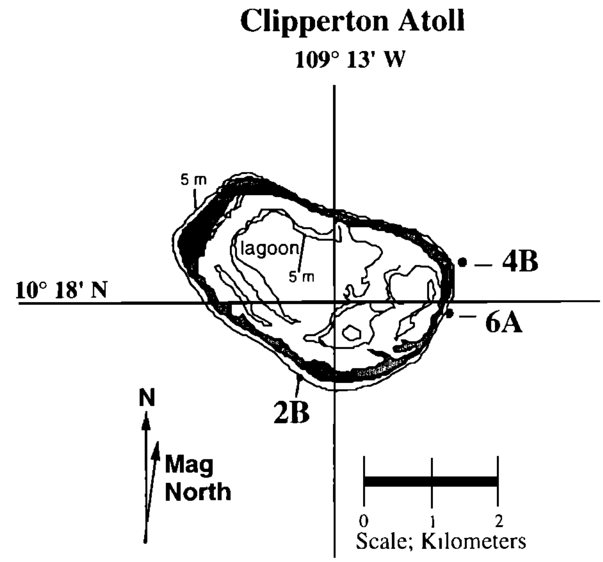
Massive corals have proven in some settings to be useful for examining past oceanographic variability, particularly at interannual timescales. Past ENSO events have been identified using the temporally varying oxygen isotopic ($\delta^{18}O$) composition of the skeletons of long-lived corals located in ENSO-sensitive settings [*McConnaughey*, 1989; *Druffel et al.*, 1990; *Cole and Fairbanks*, 1990; *Cole et al.*, 1993; *Dunbar et al.*, 1994; *Charles et al.*, 1997, *Evans et al.*, 1998]. In many cases the $\delta^{18}O$ composition of coral skeletons has proven to be a good indicator of seasonal and interannual changes in both sea surface temperature (SST) and precipitation, which in some areas, are both associated with changes in ENSO [*Dunbar and Wellington*, 1981; *Swart*, 1983; *McConnaughey*, 1989; *Cole et al.*, 1993; *Linsley et al.*, 1994; *Wellington et al.*, 1996; *Charles et al.*, 1997]. Records of this type can be used to examine past variations in the frequency or pacing of the ENSO system. It is also possible that corals may provide insight into decadal and secular changes in surface ocean properties and the relationship to ENSO, although at present, there are only several complete century length coral records that contain significant ENSO band variability. Some of these are discussed by *Cole et al.* [1993], *Dunbar et al.* [1994], and *Charles et al.* [1997]. These and other available coral $\delta^{18}O$

records suggest potential problems related to correct interpretation of decadal and long-term $\delta^{18}O$ trends. (1) An interdecadal cycle of unknown origin is commonly identified in long coral $\delta^{18}O$records [*Dunbar et al.*, 1994; *Linsley et al.*, 1994; *Charles et al.*, 1997] (2) Long-term secular trends of increasing or decreasing $\delta^{18}O$ are observed in some corals [*Dunbar et al.*, 1994; *Linsley et al.*, 1994; *Dunbar et al.*, 1996; *Charles et al.*, 1997; *Quinn et al.*, 1998; *Guilderson* and Schrag, 1999]. It is not clear whether these trends in $\delta^{18}O$ are due to biogenic processes in corals or result from gradual environmental changes. To extend our understanding of past oceanographic variability and help ground truth the composite SST reconstructions that are based on combining the sparse instrumental SST data, additional coral records need to be developed.

In this paper we present a new subseasonal 101 year coral $\delta^{18}O$ and $\delta^{13}C$ record (1893-1994) using a specimen of *Porites lobata* from Clipperton Atoll (10°18'N; 109°13'W; Figures 1 and 2). Clipperton is located on the seasonally varying boundary between the North Equatorial Current (NEC) and the Equatorial Counter Current (ECC) in a region strongly influenced by ENSO. As there are no other equatorial islands between Clipperton (109°W) and the Line Islands (160°W), corals from this site may contain unique paleoclimatic information. The objectives of this study are (1) to compare this isotopic record to two shorter (57 and 49 year) near annually averaged *P. lobata* isotopic records from Clipperton to examine reproducibility and stability of disequilibrium $\delta^{18}O$ and $\delta^{13}C$ isotopic offsets over time (2) to examine the interannual, decadal, and long-term secular trends in $\delta^{18}O$ in this off-equatorial location, and (3) to compare the Clipperton record with other published Pacific Ocean (Tarawa [*Cole et al.*, 1993] and Kiritimati [*Evans et al.*, 1998]) and Indian Ocean (Seychelles [*Charles et al.*, 1997]) coral isotopic records to examine the ENSO coupling between eastern and western Pacific and the Indian Ocean.



Location of cores used in this study.

Core #	Water Depth
2B	13.1m (43')
4B	8.2m (27')
6A	11.3m (37')

Figure 1. Site map of Clipperton Atoll in the eastern Pacific showing location of coral cores used in this study.

2. Study Area and Coral Cores

Coral cores were collected in April 1994 from Clipperton Atoll in the eastern Pacific (Figure 1). It is the easternmost atoll in the Pacific Ocean, lying ~1100 km southwest of Mexico. All sampled *P. lobata* colonies grew near the outer edge of the carbonate terrace surrounding the atoll. The total usable length of the longest core (core 4B) is 2.45 m, and the water depth at the colony top was 8.2 m. As discussed in section 3.3 this core extends from 1893 to 1994. For this study we also analyzed near annually averaged samples from two other shorter coral cores from *P. lobata* colonies at Clipperton (Figure 1). Core 2B was collected at 13.1 m water depth on the SW side of the island, has a usable length of 1.26 m, and has distinct annual density bands in the top two thirds of the core. This core spans ~1937-1994. Core 6A was collected on the NE side of the island at 11.3 m water depth and has a useable length of 1.20 m because the bottom third of the core was drilled off the main growth axis. Core 6A is poorly banded, but by comparison to 2B we estimate that the useable length spans ~1945-1994. All three cores show no evidence of growth hiatuses or growth discontinuities.

Over the last 2 decades sea SST for the 2°x2° grid box surrounding Clipperton Island has ranged mainly between 27° and 29°C with an average annual variation of ~ 2°C [*Reynolds*, 1988; *Levitus et al.*, 1994; *Reynolds and Smith*, 1994]. SST

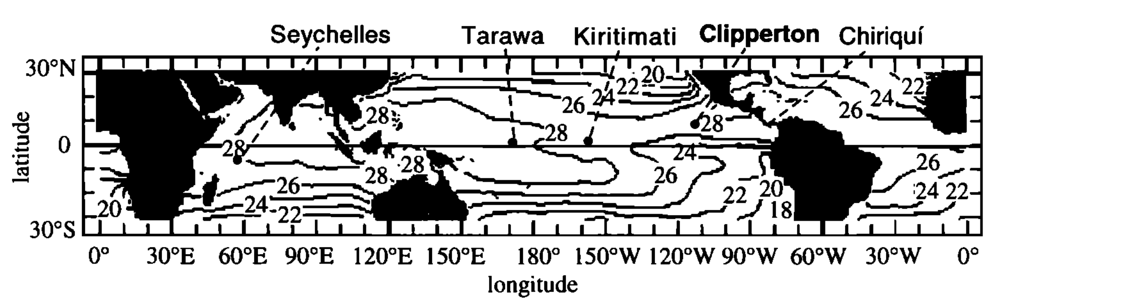


Figure 2. Annually averaged sea surface temperature from 30°N to 30°S. Data are from *Levitus and Boyer* [1994]. Also shown are the locations of Clipperton Atoll, the Gulf of Chiriquí (Panamá), Kiritimati (Christmas Island), Tarawa Atoll, and the Seychelles. See text for discussion.

maxima occur in May-June, and minima occur in January-February. Positive SST anomalies at Clipperton are generally associated with El Niño events; however, as Clipperton Atoll is located north of the Niño-3 region (defined as 6°N to 6°S, 90°-150°W), the relative magnitudes of SST anomalies during each El Niño event are different than those observed in the more equatorial Niño-3 region. For example, at Clipperton, positive SST anomalies of only 0.5°C occurred during the 1982-1983 and 1990 El Niño events, with larger 1°C anomalies during the 1972-1973 and 1986-1987 El Niño events. This pattern is opposite what is observed in the Niño-3 region.

Clipperton also has a pronounced wet season lasting from May/June to November when the Intertropical Convergence Zone (ITCZ) shifts northward [*Mitchell and Wallace*, 1990; *Spencer*, 1993] and the ECC is well developed [*Wyrtki*, 1966]. Precipitation maxima occur in August/September with an average of 120 mm/month, while precipitation minima occur in March/April with only 10 mm/month. Both precipitation maxima and minima lag the SST maxima and minima by up to 2 months. In January when the ITCZ moves toward the equator the ECC breaks up into several segments, and the NEC and California Current intensify [*Wyrtki*, 1966]. The average seasonal sea surface salinity (SSS) near Clipperton varies by <0.8‰ annually, ranging from 33.3‰ in September-December when the ECC is strongest to 34.1‰ in January-March when the NEC is strongest [*Bennett*, 1966; *Levitus et al.*, 1994]. Thus the lowest SSS at Clipperton coincides with the intensified ECC and when the ITCZ is at its most northern position. During El Niño events, Clipperton is located between zones of anomalously low and high pressure. This situation makes the precipitation pattern complicated, with more rainfall in some El Niños while other events result in drought conditions.

SST variability in the Clipperton region over the past century is poorly constrained. *Kaplan et al.*, [1998] used an optimal smoothing (OS) technique applied to the sparse instrumental SST data from this remote region to estimate monthly SST anomalies with associated error back to 1856 (Figure 3). The OS-SST anomaly results for the 5°x5° grid-box surrounding Clipperton show several 1°C decadal changes before 1920 and from 1950 to 1960 and generally cooler conditions from 1910 to 1935 (Figure 3). The errors on the SST estimate reflect the fact that this OS-SST anomaly product is based on sparse data before 1950 and particularly during the world wars.

3. Methods

3.1. Sample Preparation

The coral cores (4B, 6A, and 2B) used for this study were washed with fresh water, air dried, and then cut using a low-speed band saw into 7 mm thick slabs along the major axis of growth. Great care was taken to produce sections that were parallel to the growth axis. As a guide to sampling and chronology development, the slabs were X-rayed (30 kV, 3 Ma, and 70-90 s) with a Phillips Radifluor medical X-ray unit. Although not shown here, X-ray positives of multiple core tops from Clipperton are displayed by Linsley et al. [1999].

The slabs of coral were cleaned with deionized water in an elongate ultrasonic bath for 15 min to remove saw cuttings and were then oven dried at 40°C. For this study, subannual samples were collected for isotopic analysis by using a microdrill with a 1 mm diameter diamond drill bit under a binocular microscope along tracks parallel to corallite traces identified in X-ray positives. Core 4B was continuously sampled every 2.5 mm along the axis of maximum growth, excavating a groove ~1 mm deep and 3 mm wide. This sampling resolution was chosen to minimize the effects of numerous fish grazing skeletal scars [see *Linsley et al.*, 1999] but still capture the full range of the annual cycle. As the skeletal extension rate averaged ~25 mm/year, this procedure resulted in the recovery of an average of 10 samples per year. The reproducibility of long-term trends in $\delta^{18}O$ and $\delta^{13}C$ in *P. lobata* from Clipperton was examined through low-resolution sampling of cores 2B and 6A. Core 2B, which has distinct density bands back to 1959, was sampled on an annual average basis from 1994 to 1959 and at approximately an annual interval

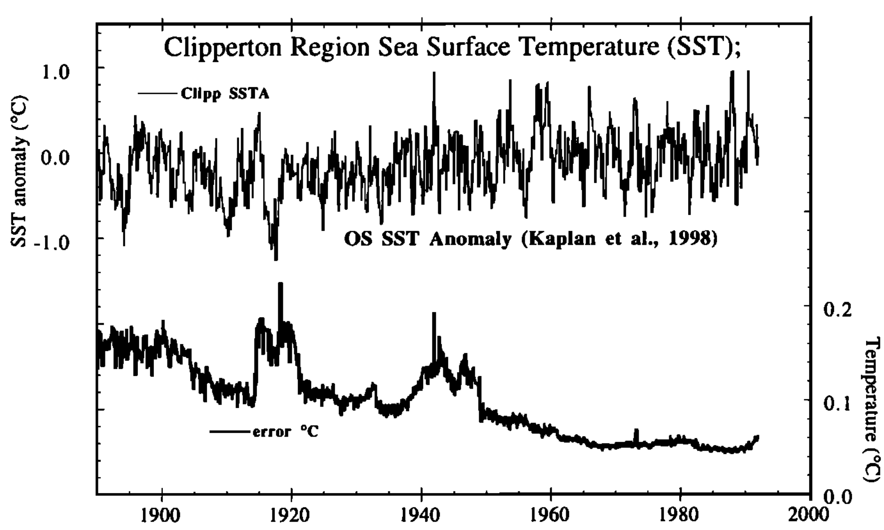


Figure 3. OS-SST anomaly (1890-1991) for the 5°x5° latitude-longitude grid box surrounding Clipperton Atoll and associated errors from *Kaplan et al.* [1998].

from 1958 to ~1937. Core 6A had a poor, indistinct density banding pattern and was sampled continuously at 2 cm intervals.

3.2. Mass Spectrometer Analysis

Approximately 200 μg samples from cores 4B and 6A were dissolved in 100% H_3PO_4 at 90°C in a Multiprep sample preparation device. The resulting CO_2 gas was analyzed using a Micromass Optima mass spectrometer at the University at Albany, State University of New York. The total number of subannual samples analyzed was 1093. Of these samples, ~10% were analyzed in duplicate. The standard deviation of 227 samples of international reference NBS-19 analyzed over a 15 month time period was 0.02‰ for $\delta^{13}C$ and 0.04‰ for $\delta^{18}O$. The average difference between duplicate analyses of the same sample (n =110) was 0.028‰ for $\delta^{13}C$ and 0.029‰ for $\delta^{18}O$. Core 2B (1994-1937) was analyzed at Rice University, where 500-1000 μg sized samples were analyzed with a semiautomated VG Micromass 602E mass spectrometer. In the Rice Laboratory the standard deviation of the NBS-19 standards analyzed over the time of these analyses was 0.05‰ for $\delta^{13}C$ and 0.06‰ for $\delta^{18}O$. The average standard deviation of the replicate samples analyzed was 0.07‰ for $\delta^{13}C$ and 0.08‰ for $\delta^{18}O$. All data are reported relative to Vienna Peedee belemnite (VPDB).

3.3. Chronology

We used the annual periodicity of skeletal $\delta^{18}O$ and $\delta^{13}C$ to develop the chronology for core 4B as described by *Linsley et al.* [1999]. This was necessary because core 4B has indistinct density bands. We first determined that these skeletal $\delta^{18}O$ and $\delta^{13}C$ cycles were annual. Counting $\delta^{18}O$ and $\delta^{13}C$ cycles results in a total of 101 years in this record. This places large negative $\delta^{18}O$ anomalies in the record during the intervals 1918-1920, 1930, 1957-1958, 1972-1973, and 1990-1991 when there were strong ENSO events and positive SST anomalies at Clipperton (using Climate Analysis Center SST [*Reynolds and Smith,* 1994] and OS-SST [*Kaplan et al.,* 1998]). The 1976 cold event is also clearly identified in the record. As this coral was collected live from Clipperton in April 1994, a date of early 1994 is assigned to the outer surface of the coral, and the last year is counted down to 1893.

Even though it is known that coral $\delta^{18}O$ variations at Clipperton are related to both SST and SSS variations [*Linsley et al.,* 1999], the 2°C annual SST range should still be useful as a chronometer. We refined this chronology by retuning this $\delta^{18}O$ data to the monthly SST record by assigning the lowest $\delta^{18}O$ in a given year to the month of highest SST and the highest $\delta^{18}O$ to the lowest SST using the available SST data from 1970 to 1994. For all other age assignments before 1970 the lowest $\delta^{18}O$ extremes were assigned to May of each year (on average, the highest SST month), and the highest $\delta^{18}O$ extremes were assigned to January of each year (similarly, on average, the month of lowest SST), and we interpolated linearly between these anchor points for all other age assignments. Since the precise timing of highest and lowest SST may vary from year to year, this approach may create the potential for a 1 to 2 month timescale error in any given year. Also, because the SST maximum and the salinity minimum are lagged by ~2 months, it is possible that the combination of SST and SSS have broadened the seasonal cycle recorded in coral $\delta^{18}O$.

The chronology for the annually averaged data from core 2B was developed on the basis of the distinct annual density bands from 1994 to 1959. In the less distinctly banded interval below we have estimated the chronology on the basis of the less distinct bands and by comparison to core 4B $\delta^{18}O$. As presented here, the total 2B record spans 1994-1937. The chronology for the poorly banded core 6A was developed by comparison to the results from 2B and 4B over the period 1994 to ~1945. We have plotted data from 6A and 2B at one per year and at the midpoint of that year. We are less certain of the chronology of 6A and also 2B because of the possibility of collecting samples from adjacent years of growth and/or from part of a year. In addition, there is also the possibility that the small subsamples analyzed for $\delta^{18}O$ and $\delta^{13}C$ may not always have been representative of the entire sample.

Subannual age estimates for core 4B were linearly interpolated into 12 points per year using the "Arand" series of programs (P. Howell, personal communication, 1998). Although 12 points per year exceeds the average raw sample density of ~10 per year, this increase facilitates comparison to monthly instrumental data and does not appear to effect interpretation of the results. For example, in experiments where annual averages of 4B $\delta^{18}O$ were calculated from deseasonalized series of both 10 and 12 samples per year, the resulting annually averaged series were virtually identical.

3.4. Time Series Analysis

A singular spectrum analysis (SSA) software program written by E. Cook (Lamont-Doherty Earth Observatory) was used in the analysis of the coral and climate time series. A detailed description of this technique and its paleoclimate application is given by *Vautard and Ghil* [1989] and *Vautard et al.* [1992]. SSA has been previously applied to coral time series [*Dunbar et al.,* 1994; *Linsley et al.,* 1994; *Charles et al.,* 1997]. SSA is a fully nonparametric analysis technique based on principal component analysis of delay coordinates in vector space for a time series. It uses M lagged copies of a centered time series to calculate eigenvalues and eigenvectors of their covariance matrix. Reconstructed components (RCs) are then calculated, which allow a unique expansion of the signal into its different frequency components. SSA analysis of the 4B $\delta^{18}O$ data was run multiple times at different values of M. Values of M between 48 months and 144 months did not significantly influence recognition of the dominant oscillatory modes. For the results presented here an M of 72 months was selected.

4. Results

4.1. Oxygen and Carbon Isotopes

On the basis of analysis of multiple specimens of *P. lobata* at Clipperton, *Linsley et al.* [1999] found that the $\delta^{18}O$ offset from equilibrium composition (so-called vital effect) can vary by up to 0.4‰. This range in vital effect offset is even observed in *P. lobata* specimens growing at the same water depth and in close proximity. *Guilderson and Schrag* [1999] found a similar (nearly constant) $\delta^{18}O$ offset in two adjacent *Porites* colonies in Naru. *Linsley et al.* [1999] concluded that the 0.4‰ variation in disequilibrium offset is most likely due to core sampling location on a dome- shaped colony as has been shown by *Pätzold* [1984, 1986]. They also concluded that relative $\delta^{18}O$ variations are more significant in comparing multiple coral isotopic records and recommended centering (removal of mean) of individual $\delta^{18}O$ time series before comparisons. We have adopted this approach here.

The down-core 4B $\delta^{18}O$ (PDB) results and the annually averaged and centered results from 2B and 6A show similar secular and decadal trends (Figure 4a). However, the $\delta^{13}C$ results from the same cores have different amplitude carbon isotopic

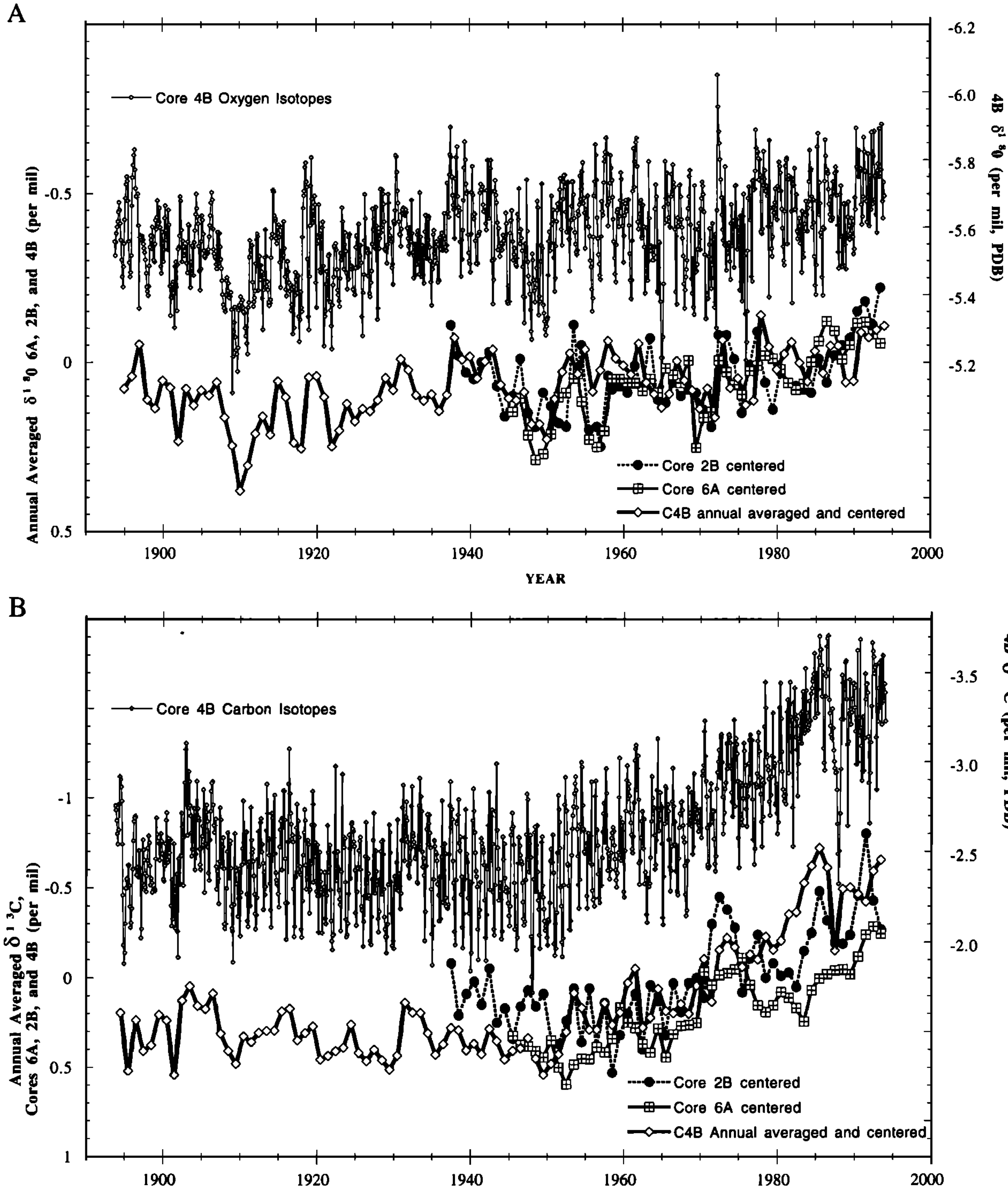


Figure 4. (a.) Clipperton core 4B subseasonal $\delta^{18}O$ (relative to Peedee belemnite (PDB)) spanning 1893-1994 (top curve) and annually averaged $\delta^{18}O$ results (centered) from core 2B (1937 -1994), 2 cm $\delta^{18}O$ results (centered) of core 6A (1945-1994), and annual binned core 4B $\delta^{18}O$ (bottom curves). For all three $\delta^{18}O$ records the average over the interval from 1970 to 1994 was removed. (b.) Clipperton core 4B subseasonal $\delta^{13}C$ (top curve) and annually averaged $\delta^{13}C$ results (centered) from core 2B (1994 to 1937), 2 cm $\delta^{13}C$ results (centered) of core 6A (1994-1945), and annual binned core 4B $\delta^{13}C$ (bottom curves).

Table 1. Singular Spectrum Analysis for Clipperton Atoll: Unfiltered $\delta^{18}O$ Series 1893-1994

Eigenvector	Variance,%	Cumulative Variance, %	Mean Period, year
1	26.2	26.2	trend
2	9.0	35.2	11.9
3, 4	16.3	51.5	1
5	6.2	57.7	6.4
6	4.5	62.2	4.0
7-15	18.2	80.4	<3

Here $\delta^{18}O$ (n =1203) and M=72 months (data unfiltered).

trends, although they are all of the same sense to lower $\delta^{13}C$ after ~1970 (Figure 4b). In the centered $\delta^{18}O$ and $\delta^{13}C$ data the mean from the interval spanning 1970-1994 was removed from each PDB record. The annually averaged results from core 4B in the lower half of Figures 4a and 4b were calculated by annual binning of the monthly 4B 2.5 mm dataset following removal of the seasonal cycle by band-pass filtering. The decadal and secular trends in the annually averaged $\delta^{18}O$ data from core's 2B and 6A are generally in agreement with annually binned $\delta^{18}O$ from core 4B. The exception occurs in 1956-1958 where core 4B is ~0.15‰ depleted in ^{18}O relative to cores 2B and 6A. The origin of this offset is unknown but is possibly an artifact of the coarse sampling technique. Given the limitations of the age models for cores 2B and 6A, the main conclusion that can be derived from comparison of these three $\delta^{18}O$ records is that all three cores show similar long-term (secular) trends of -0.3‰. As the colonies are of different ages, this suggests that the -0.3‰ $\delta^{18}O$ trend may not be biologically mediated but rather is due to external environmental change.

4.2. Frequency Analysis

To more precisely identify and assess the pacing and amplitude of the interannual and interdecadal $\delta^{18}O$ variations, SSA was used to determine the dominant mean frequencies of increased variance in the $\delta^{18}O$ time series. For the unfiltered data the 15 most significant eigenvectors and their associated variance and mean periods are listed in Table 1. The relatively small percentage of variance explained by the annual cycle (16%) is apparently due to the small annual SST range in this warm region of the eastern Pacific. To isolate the interannual and interdecadal periodicities in the $\delta^{18}O$ record, the analysis was repeated after first applying a band-pass filter to remove periods <2 years. The results of this analysis are presented in Table 2. With the removal of frequencies <2 years, seven leading eigenvectors (EOFs) are recognized. The first eigenvector explains over half of the variance and represents a long-term or secular trend of the full record. The second eigenvector (mean period is 12.5 years) contributes 17.3% to the total variance. The third, fourth, and fifth eigenvectors isolate the interannual changes which are all in the ENSO band and represent 12.1%, 7.6%, and 3.9% of the total variability, respectively. The last two eigenvectors have mean periods near 2 years.

5. Discussion

5.1. Oxygen Isotopes: Comparison With an Historical Record of ENSO and With OS-SST anomaly

In a previous study, *Linsley et al.* [1999] have shown that at Clipperton annual and interannual variations in *P. lobata* skeletal $\delta^{18}O$ spanning 1970-1994 is the result of a combination of varying SST and $\delta^{18}O_{seawater}$ related to the annual cycle and ENSO. They concluded that skeletal $\delta^{18}O$ can be used to reconstruct the

Table 2. Singular Spectrum Analysis for Clipperton Atoll: Filtered $\delta^{18}O$ Series 1893-1994

Eigenvector	Variance, %	Cumulative Variance, %	Mean Period, year
1	53.9	53.9	Trend
2	17.4	71.3	12.5
3	12.1	83.4	6.5
4	7.6	91.0	3.9
5	3.9	94.9	2.9
6	2.4	97.3	2.2
7	1.5	98.8	2.0

Here $\delta^{18}O$ (n =1203) and M=72 months (data filtered at 2 years).

recurrence of past El Niño events at this site even though the magnitude of El Niño-related increases in SST near Clipperton is much smaller than found in the more equatorial Niño-3 region. Because the ENSO event frequency band is ~3-8 years [*Trenberth*, 1976; *Rasmusson et al.*, 1990; *Barnett*, 1991], to assess how ENSO band variability recorded in this off-equatorial axis site compares to a more well-known ENSO index, we summed Clipperton 4B $\delta^{18}O$ ENSO band RCs (RCs 3, 4, and 5 in Table 2) and compare the result to the Southern Oscillation Index (SOI) (Figure 5a). Although the timing and relative amplitude of ENSO events are similar in both records, notable exceptions include ENSO events in 1904-1905, 1926-1927, 1940, and 1982-1983, where the Clipperton record shows no or little response. This highlights the different signature of ENSO in this off-axis (10°N) location. Past "El Niño event years" identified by *Quinn et al.* [1987] and *Quinn* [1992] on the basis of coastal historical evidence are included for reference. Most of the El Niño events reconstructed from historical archives can be identified in the 4B $\delta^{18}O$ ENSO band RCs. Of the 24 documented El Niño events in the period from 1893 to 1994 [*Quinn et al.*, 1987; *Quinn* 1992], 19 are clearly observed in core 4B $\delta^{18}O$. El Niño events not clearly expressed in core 4B are the 1904-1905, 1925-1926, 1940, 1953 and 1982-1983 events.

In an attempt to determine to the temporally varying influence of SST and SSS on coral $\delta^{18}O$ at Clipperton and also to test the reliability of the coral and composite OS-SST anomaly records, we have compared core 4B $\delta^{18}O$ ENSO band RCs to the combined ENSO band SSA RCs of the 5°x5° OS-SST anomaly series from the Clipperton region [*Kaplan et al.*, 1998](Figure 5b). For this analysis of OS-SST anomaly only the portion from 1893 to 1991 was analyzed with the same settings as the band-pass filtered core 4B $\delta^{18}O$ results with the results scaled by 25% to allow plotting on roughly equivalent scales. In general, the amplitude of the ENSO band variability in both coral $\delta^{18}O$ and OS-SST anomaly agree, with higher amplitude variations from 1893 to 1925 and from 1955 to 1980. However, the phasing between each ENSO band

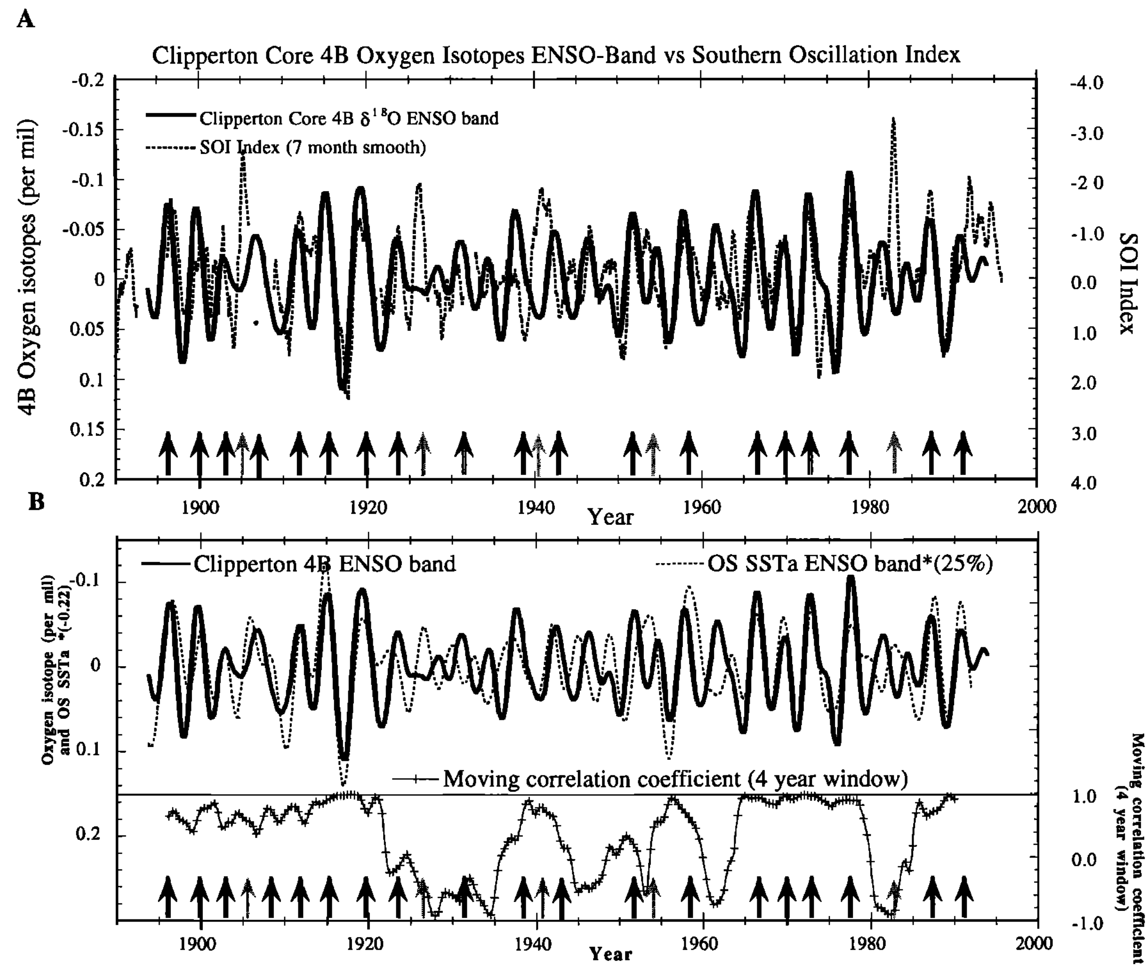


Figure 5. a.) Comparison of singular spectrum analysis (SSA) extracted ENSO band RCs from Clipperton core 4B $\delta^{18}O$ (this study) and the Southern Oscillation Index (SOI). Arrows denote times of noted El Niño events [*Quinn et al.*, 1987; *Quinn*, 1992], with thick arrows indicating El Niños recorded in Clipperton coral $\delta^{18}O$ and thin arrows indicating El Niño's not recorded in Clipperton coral $\delta^{18}O$. b.) Comparison of SSA extracted ENSO band Reconstructed Components (RCs) from Clipperton core 4B $\delta^{18}O$ (this study) and OS-SST anomaly [*Kaplan et al.*, 1998] for the 5°x5° grid box surrounding Clipperton. The bottom curve is the moving correlation coefficient (4 year window) showing the phasing between core 4B $\delta^{18}O$ and OS-SST anomaly. Arrows denote El Niños as in Figure 5a.

record varies significantly (Figure 5b, bottom curve). The moving correlation window highlights the intervals where the two series are well correlated and also times where they are less well or inversely correlated. Intervals of poor or inverse correlation include ~1924-1935, ~1945-1955, 1960-1963, and ~1980-1984. During these times it is possible that changes in salinity had a larger effect on coral $\delta^{18}O$ than SST. Of the five El Niño events noted by *Quinn et al.* [1987] and *Quinn* [1992] but which are not observed in Clipperton coral $\delta^{18}O$, only the 1925-1926 and 1982-1983 El Niños are expressed as positive SST anomalies in the OS-SST anomaly series.

In summary, because Clipperton Atoll is located outside of the Niño-3 region, the amplitudes of SST anomalies during ENSO events in this off-axis location are often different than in the equatorial Niño-3 region. The time history of ENSO band variability from Clipperton indicates that ENSO events were relatively strong before 1920 and between 1950 and 1980, while between 1925 and 1950 they were relatively weak.

5.2. Oxygen Isotopes: ENSO Band Comparison With Other Coral Records

Comparison of coral time series from several ENSO sensitive areas provides the opportunity to examine the interannual climatic coupling between the eastern and western Pacific Ocean and between the Pacific and Indian Oceans. In this section we compare the Clipperton $\delta^{18}O$ ENSO band RCs with the $\delta^{18}O$ ENSO band RCs of coral records from Kiritimati [*Evans et al.*, 1998], Tarawa Atoll [*Cole et al.*, 1993], and the Seychelles [*Charles et al.*, 1997] (see Figure 6). Tarawa Atoll (1°N, 172°E) is located in the western Pacific and lies on the eastern edge of the western Pacific warm pool in a region where large positive rainfall anomalies are generated during an El Niño event by the eastward migration of the Indonesian Low [*Cole et al.*, 1993]. This record spans 1991-1893. Kiritimati at 2°N and 157°W is located in the equatorial central Pacific, a region where oceanographic variability is strongly tied to ENSO. This coral record spans the interval 1994-1938 [*Evans et al.*, 1998; 1999]. The Seychelles (5°S, 56°E) are located in the southwest Indian Ocean, an area recognized as sensitive to the Asian monsoon and ENSO. This coral record extends from 1995-1846 [*Charles et al.*, 1997]. Here we use that portion from 1893 to 1995, comparable to the lengths of the Clipperton and Tarawa $\delta^{18}O$ records.

The Kiritimati record shows much larger amplitude ENSO band $\delta^{18}O$ variability than Clipperton, reflecting the larger ENSO-related SST anomalies in this region (Figure 6a). Examination of the moving correlation window shows that the Clipperton and Kiritimati ENSO band records are generally in phase in the 1950s and 1970s and are notably out of phase in the early 1960s and 1980s. This comparison also indicates that the 1940-1941 and 1982-1983 El Niños were more focused in the central Pacific and equatorial areas with little expression near Clipperton, an observation that agrees with instrumental records. Tarawa $\delta^{18}O$ ENSO band RCs also exhibit much larger amplitude ENSO-related variations than Clipperton, but both series have similar variations in ENSO amplitude over time (Figure 6b). Before 1925 and after 1960, the ENSO amplitudes in each series are larger than those between the ~1925-1940 period. The moving correlation coefficient reveals that both the Clipperton and Tarawa records are generally in phase before 1925, from ~1945 to 1960, and from 1963 to 1975. This may imply that during these periods the eastern and western Pacific displayed relatively good climatic coupling. The opposite is observed during 1925-1945 and 1976-1984 where Tarawa and Clipperton coral $\delta^{18}O$ variability is generally out of phase. The comparison of the ENSO band $\delta^{18}O$ variability preserved at Clipperton and the Seychelles also shows notably out of phase behavior in the late 1920s and again in the early 1980s as well over several other short intervals. However, the Seychelles coral $\delta^{18}O$ record does not display significant reduced ENSO amplitudes in the 1920s through 1950s as observed in Clipperton and Tarawa.

The reduced correlation between the Tarawa and Clipperton $\delta^{18}O$ records from 1925 to ~1945 agrees with the findings of *Trenberth and Shea* [1987]; *Elliott and Angell* [1988], *Cooper and Whysall* [1989], *Pan and Oort* [1990], *Enfield and Cid* [1991], *Allan* [1993], *Tudhope et al.* [1995], and *Allan et al.* [1996]. All observed to varying degrees a similar phenomenon where from ~1925 to the mid-1940s the correlation between atmospheric pressures (SO indices) and SSTs was relatively low. This unexplained example of ENSO background state changes has been observed to be a time of weak ENSO indices and reduced coupling between the eastern and western Pacific. Through examination of New Guinea coral isotopic records, *Tudhope et al.* [1995] also noted variability in the degree of coupling of the climate of the west Pacific with the Southern Oscillation and suggested that from the 1920s to 1950s the western equatorial Pacific was less important in modulating Pacific and global interannual climatic variability than it has been since the 1950s. The results presented here support this contention.

5.3. Oxygen Isotopes: Decadal Changes

An interesting aspect of the Clipperton 4B $\delta^{18}O$ time series is that decadal variability (isolated in RC 2, Table 2) is greater in strength than the ENSO band variability (split between RCs 3 and 4). Now that it is known that ENSO may contribute and/or respond to decadal-scale variability in the subtropics [*Gu and Philander*, 1997; *Guilderson and Schrag*, 1998; *Zhang et al.*, 1998], it is important to try an understand the source of decadal-scale changes found in this and other coral proxy records. Correlation of annually averaged Clipperton coral $\delta^{18}O_{anomaly}$ (deseasonalized) and Clipperton OS-SST anomaly against global OS-SST anomaly reveals a broad region of positive correlation in the eastern and central tropical Pacific and a negative correlation with both North Pacific and South Pacific gyre regions (Figures 7a and 7b). The regions of positive correlation are not equatorially "trapped" but rather extend into the midlatitudes, particularly in the northeast Pacific. This correlation pattern is similar to the pattern that emerges when the leading eigenvector of North Pacific SST is regressed against Pacific SST [*Mantua et al.*, 1997; *Zhang et al.*, 1997]. The time history of this leading eigenvector has been termed the Pacific Decadal Oscillation (PDO) by *Mantua et al.*, [1997]. The PDO (which is also referred to as the North Pacific Interdecadal Oscillation or NPO [*Gershunov et al.* 1999]) appears to be a robust, recurring pattern of ocean-atmosphere climate variability identified in the North Pacific [*Latif and Barnett*, 1994a,b; *Minobe*, 1997; *Mantua et al.*, 1997; *Gershunov et al.*, 1999]. The phases can last 2-3 decades. The similarity between the PDO and Clipperton $\delta^{18}O$ correlation

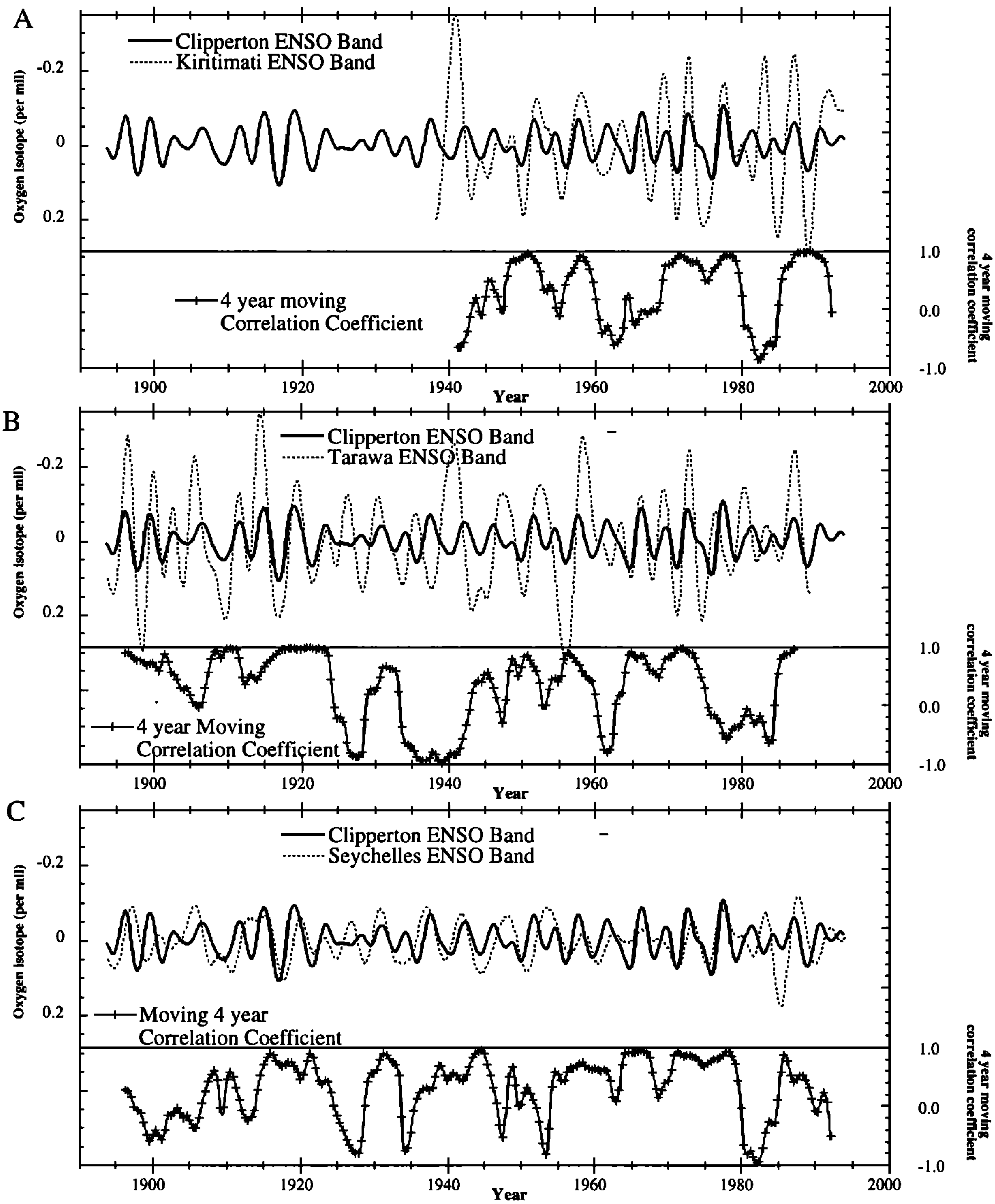


Figure 6. Comparison of SSA-extracted coral $\delta^{18}O$ ENSO band variability at Clipperton Atoll with coral-derived ENSO band variability at (a) Kiritimati [*Evans et al.*, 1998], (b) Tarawa [*Cole et al.*, 1993], and (c) the Seychelles [*Charles et al.*, 1997]. The bottom curve in each plot is moving correlation coefficient (4 year window) between series in each plot.

fields suggests that SST and/or salinity variability near Clipperton are related to the processes influencing the PDO. *Mantua et al.* [1997] have defined a PDO index based on North Pacific SST, such that when it is cooler than average in the central North Pacific and warmer than average in the Gulf of Alaska and along the Pacific Coast of North America, the index is positive. These periods tend to correspond with warm phases of ENSO. La Niña years correspond with the negative phase of the index when the central North Pacific is warmer than average and the coastal waters of the NE Pacific are cooler than average.

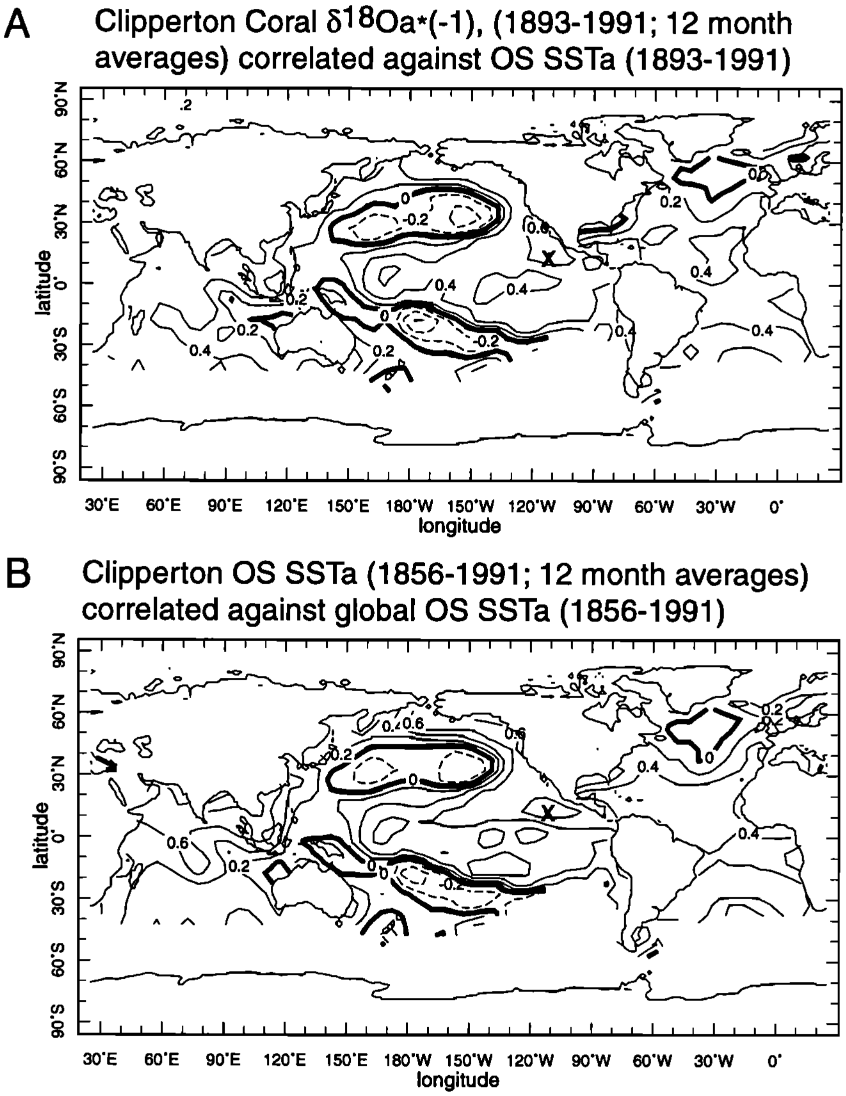


Figure 7. a.) Correlation of Clipperton coral oxygen isotopic composition anomaly ($\delta^{18}O_{anomaly}$ multiplied by -1) (1893-1991) against global OS-SST anomaly. Clipperton location is shown by cross. Dashed contours equal negative correlation. (b) Correlation of Clipperton Atoll OS-SST anomaly (1856-1991) against global OS-SST anomaly (data are from *Kaplan et al.*, [1998]). The correlation fields have a similar pattern to the large-scale Pacific Decadal Oscillation (PDO) pattern (see text for discussion).

Further evidence of the PDO influence at Clipperton is apparent when the sum of the trend, decadal, and interannual RCs of Clipperton $\delta^{18}O$ and OS-SST anomaly are compared to the PDO Index (Figures 8a and 8b). In this plot, $\delta^{18}O$ has been scaled so that 0.31‰ equals 1°C, which is the slope of the regression relationship for the average of three 20 year coral $\delta^{18}O$ records regressed against SST at Clipperton [see *Linsley et al.*, 1999]. There are three intervals (1926-1944, ~1950-1960, and 1976-1994) where coral $\delta^{18}O$ values are ~0.2-0.3‰ lower than expected if SST was the main source of coral $\delta^{18}O$ variability, with the 1926-1944 and the post-1976 interval showing the lowest $\delta^{18}O$ values. We interpret these intervals to be times of lower $\delta^{18}O_{seawater}$ (lower salinity) at Clipperton. This assumes that the mean annual OS-SST anomaly is accurate in these intervals and is representative of local SST anomaly at Clipperton. Furthermore, we suggest that these intervals are times of intensified ECC, which are associated with relatively lower salinity in the eastern Pacific than the NEC due, in part, to its association with the ITCZ [*Bennett*, 1966; *Wyrtki*, 1966; *Levitus et al.*, 1994]. The ECC is a geostrophic current moving eastward across the Pacific in the sea surface topographic "trough" between the southeast and northeast trade wind belts. In the eastern Pacific its flow is most intense from June to November of each year. An intensification of the ECC in these intervals implies that the mean position of the ITCZ was also more northerly than present at these times. For the interval from 1926 to 1944 this interpretation seems to agree with the observation of reduced ENSO variability throughout this period. A decade of reduced ENSO behavior should correspond with stronger trade winds and a stronger ECC.

In an attempt to isolate the degree of decadal ITCZ variability at Clipperton we compare the SSA extracted decadal and trend modes from the Gulf of Chiriquí (Panamá) coral $\delta^{18}O$ record

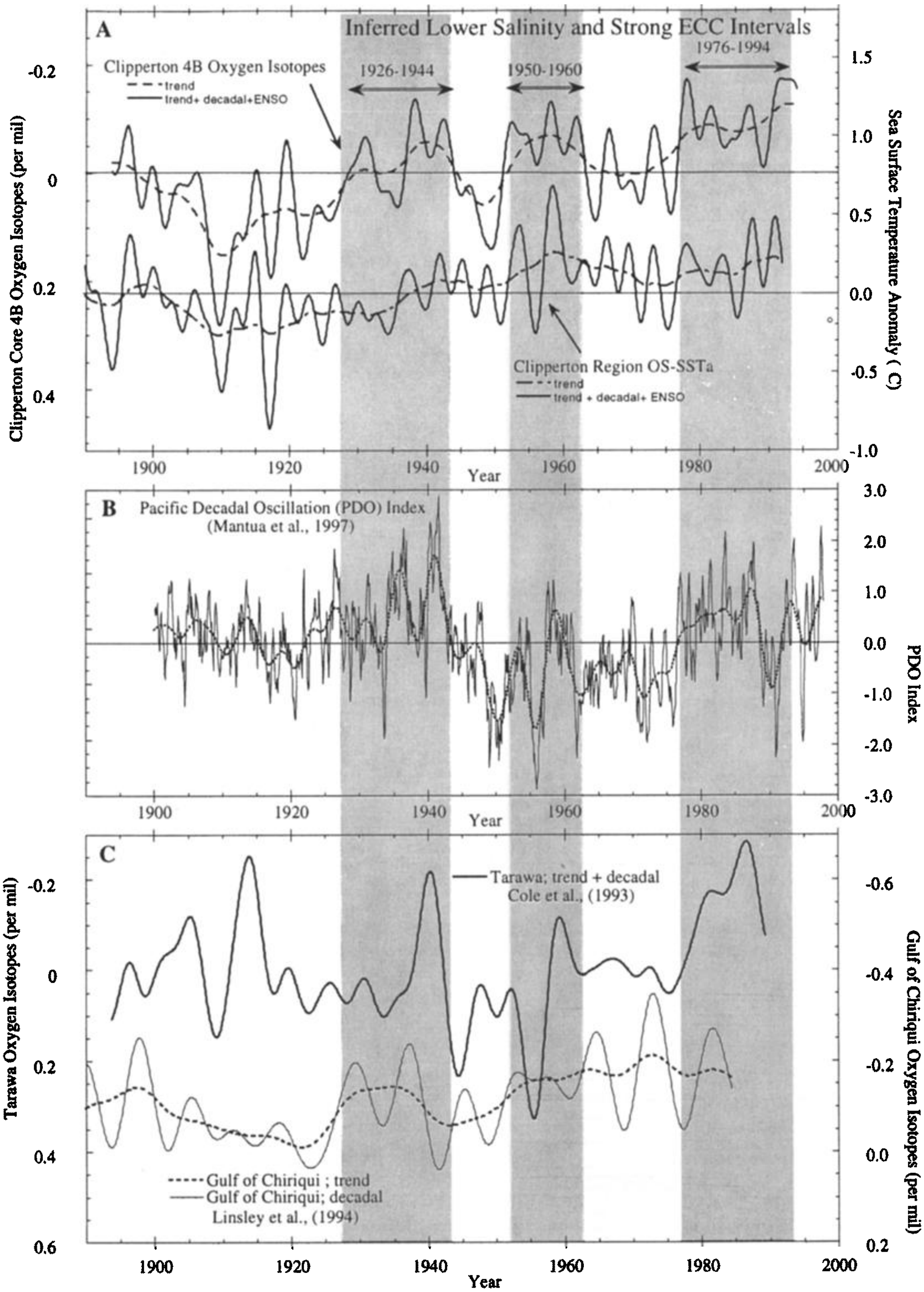


Figure 8. (a) Comparison of interannual, decadal, and secular trends in Clipperton coral core 4B $\delta^{18}O$ with those in OS-SST anomaly for the 5°x5° grid box surrounding Clipperton Atoll. See text for discussion of inferred low-salinity intervals (1926-1944, 1950-1960, and after 1976) during times of stronger Equatorial Counter Current. (b) PDO Index from *Mantua et al.* [1997]. (C) Gulf of Chiriquí [*Linsley et al.,* 1994] coral $\delta^{18}O$ decadal and secular trends spanning the same interval as the Clipperton record. See text for discussion.

[*Linsley et al.*, 1994] to Clipperton and the PDO Index (Figure 8c). The Gulf of Chiriquí coral record is thought to more directly preserve ITCZ variability via coastal runoff [*Linsley et al.*, 1994]. The Gulf of Chiriquí also shows an interval of low $\delta^{18}O$ (interpreted as high rainfall and more intense ITCZ) from 1925 to 1940. However, this is followed by a drier period until 1950, then a wetter time with pronounced decadal changes after 1950 that do not match the decadal changes at Clipperton. The lack of a more robust correspondence between all decadal changes in $\delta^{18}O$ records from Clipperton and the Gulf of Chiriquí, we suggest, also indicates that overall, the ECC is the more dominant source of the observed decadal variability at Clipperton, with the exception of 1925-1940 when the similarity of decadal changes in the two records suggests a stronger eastern Pacific ITCZ over this period.

5.4. The Long-Term "Secular" Trend in $\delta^{18}O$

The largest component of variance in the Clipperton $\delta^{18}O$ record is the long-term trend (see Tables 1 and 2 and Figure 8a). As can be seen from Figure 4, the $\delta^{18}O$ values in core 4B have decreased by ~0.3‰ over the whole record. This range of $\delta^{18}O$ variation in Clipperton core 4B is approximately the same as observed in coarser resolution sampling of Clipperton cores 6A and 2B over the period from 1940 to 1994 (see Figure 4a). The consistent amplitude of the $\delta^{18}O$ long-term trend in three coral colonies of different ages at Clipperton suggests that there has been little long-term drift of the biologically mediated $\delta^{18}O$ vital effect over this time period. However, although the pattern of this long-term trend in 4B is similar to that of the instrumental SST record, especially for the periods before 1915 and after ~1950 (see Figure 8a), the magnitude of the isotopic trend is larger than predicted by the 0.5°-0.6°C warming trend in the OS-SST anomaly series and suggests a long-term salinity change or some unknown coral growth effect affecting three *Porites* colonies of different ages. Other evidence for eastern Pacific warming is presented by *Roemmich and McGowan* [1995] and *McGowan et al.* [1998] who document a 1.5°C warming in the California Bight area since 1951. Furthermore, *Cane et al.* [1997] demonstrate that the warming covers a wide region of the eastern Pacific.

We note that a similar magnitude $\delta^{18}O$ trend was observed in the $\delta^{18}O$ data from the Seychelles Islands in the southwestern equatorial Indian Ocean [*Charles et al.*, 1997]. These authors also reported a larger inferred warming based on coral $\delta^{18}O$ than the actual SST increase. Since both Clipperton and the Seychelles are within the tropical atmospheric convergence zone, one possibility is that the additive effects of higher SST and lower salinity (lower $\delta^{18}O_{seawater}$) have contributed to the observed long-term trends. However, currently, there is no direct measurement of the variation of $\delta^{18}O_{seawater}$ from both areas to demonstrate this interpretation. Alternately, it is possible that coral growth effects and/or changes in kinetic fractionation as a colony ages could be the cause, although the comparison of $\delta^{18}O$ records from different age colonies presented here (see Figure 4a) seems to indicate that growth effects on secular $\delta^{18}O$ trends in *Porites* are minimal.

5.5. Carbon Isotopes

Although the primary focus of this report is the Clipperton coral $\delta^{18}O$ results, we believe it important to briefly discuss the $\delta^{13}C$ results. Annual variations in skeletal $\delta^{13}C$ in core 4B show a range of 0.6-0.7‰ (Figure 4b). As described by *Linsley et al.* [1999], at Clipperton the highest coral $\delta^{13}C$ values in a given year occur during the times of lowest SST when there is sparse cloud cover and, most likely, the highest rates of photosynthesis. This pattern is in agreement with the idea that the $\delta^{13}C$ of a coral skeleton reflects the level of photosynthetic activity of symbiotic zooxanthellae in coral tissue with maximum annual photosynthetic activity coincident with the most ^{13}C enriched portions of the skeleton [*Goreau*, 1977; *Erez*, 1978; *Fairbanks and Dodge*, 1979; *Swart*, 1983; *Pätzold*, 1984; *McConnaughey*, 1989; *Swart et al.*, 1996]. This pattern is also in agreement with the findings of *Grottoli and Wellington* [1999] who observed that simultaneous decreases in light and zooplankton (heterotrophy) resulted in decreased skeletal $\delta^{13}C$. Unlike $\delta^{18}O$, the amplitude of the secular trends in $\delta^{13}C$ in cores 4B, 2B, and 6A vary significantly although all trends are of the same sense (becoming lower or more negative toward the top of each core). In 4B from 1893 to 1994 the annual average $\delta^{13}C$ decreases 0.85‰ (from -2.35‰ (PDB) to -3.2‰ (PDB)), whereas 2B and 6A show smaller amplitude trends in $\delta^{13}C$. The differences observed here between $\delta^{13}C$ records from corals in close proximity suggests colony-specific effects on the $\delta^{13}C$ composition of the skeleton in agreement with the results of *Guilderson and Schrag* [1999].

6. Summary

We have developed a 101 year coral $\delta^{18}O$ and $\delta^{13}C$ record (1893-1994) from Clipperton Atoll using a specimen of *Porites lobata*. The $\delta^{18}O$ record contains strong interannual cycles reflecting ENSO events as well as other interdecadal cycles and a long-term secular trend. Comparison of this $\delta^{18}O$ record to two shorter *P. lobata* $\delta^{18}O$ records from Clipperton indicates that the three records have the same secular $\delta^{18}O$ trend. This also appears to indicate that at this site the coral $\delta^{18}O$ disequilibrium offset (vital effect) has remained constant over the life of these colonies. The pattern of the secular trend of $\delta^{18}O$ is similar to that of the instrumental OS-SST anomaly for the Clipperton region; however, the magnitude of the $\delta^{18}O$ trend is nearly twice as large as that expected if SST was the direct cause, suggesting a long-term change in salinity associated with SST warming.

Comparison of the ENSO frequency components in coral $\delta^{18}O$ with the historical records of ENSO and SST shows that the coral $\delta^{18}O$ record at Clipperton is generally sensitive to ENSO variability, although it also shows some local characteristics and underestimates several El Niño events. In agreement with instrumental records both Clipperton (this study) and Tarawa [*Cole et al.*, 1993] century length coral $\delta^{18}O$ records show reduced ENSO band variability in the period from 1925 to the mid-1940s, independently adding support to the conclusion that there was reduced ENSO event amplitudes during this time. The Clipperton $\delta^{18}O$ results also contain strong decadal variability, which we suggest is due to salinity changes related to changes in the relative strengths of the Equatorial Counter Current and North Equatorial Current. Some of this variability appears to coincide with variations in North Pacific SST and the Pacific Decadal Oscillation. We further suggest that the period of reduced ENSO variability from 1925 to the late 1930s was associated with an intensification of the Equatorial Counter Current and the eastern Pacific ITCZ.

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