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DETECTION OF EL NINO AND DECADE TIME SCALE VARIATIONS OF SEA SURFACE TEMPERATURE FROM BANDED CORAL RECORDS: IMPLICATIONS FOR THE CARBON DIOXIDE CYCLE

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Abstract. Stable oxygen isotope ratios from annually banded corals are correlated with historical records of sea surface temperature in the central and eastern tropical Pacific Ocean. El Nino events between 1929 and 1976 are detected using this method, but there are discrepancies between the records of El Ninos from corals and those determined using historical hydrographic and meteorologic data. The average annual depletion of $\delta^{18}O$ during El Nino events is greater at the Galapagos Island sites (0.45°/oo) than at the Fanning and Canton Island sites in the mid-Pacific (0.20-0.30°/oo and <0.2°/oo, respectively). Of prime importance is evidence of decade time scale variability of sea surface temperature (SST) in the tropical Pacific. In particular, annually averaged SST appears to have been 0.5°-1°C higher in the eastern tropical Pacific during the 1930's than during subsequent years. A significant net flux of CO_2 from the surface ocean to the atmosphere is envisioned during these periods of higher SST.

Introduction

Prior to the intervention of man, the pressure of CO_2 in the atmosphere (pCO_2) varied throughout geologic time. Neftel et al. [1982] provided evidence that during the height of the last glaciation, pCO_2 was about 210 ppm or about one-third less than the 19th century value (270-280 ppm). Stauffer et al. [1984] showed strong evidence of 50 ppm variations during the glacial period over very short time periods, of the order of 100 years or more. It seems unlikely that the shelf hypothesis proposed by Broecker [1982] could explain excursions on so short a time scale, as it is envisioned that significant storage of organic matter on the continental shelves could only occur over a period of thousands of years. A more plausible mechanism to explain rapid changes in pCO_2 is change in upper ocean circulation, which would cause changes in the physical and chemical properties of the surface ocean and most likely induce changes in nutrient utilization [Wenk and Siegenthaler, this volume; Toggweiler and Sarmiento, this volume].

Recent evidence linking shifts in pCO_2 to short-term changes in ocean circulation (in particular, SST) have been presented by several authors [Bacastow et al., 1980, 1981a, b; Schnell et al., 1981; Gammon et al., 1984]. These observations imply that net fluxes of CO_2 from ocean to atmosphere (1-3 metric gigatons (Gt) C/yr) are the result of widespread changes in SST (+1°-2°C) throughout the Pacific.

Influence of SST excursions on the flux of CO_2 may be particularly important in the equatorial regions of the world oceans. Pre-anthropogenic $\Delta^{14}C$ levels in the tropical Pacific were 15-30°/oo lower than at higher latitudes (Figure 1) due to upwelling of ^{14}C-depleted waters from subsurface depths. Keeling et al. [1965] showed that pCO_2 levels in these equatorial surface waters are 40-80 ppm above atmospheric equilibrium values. This is the result of an imbalance between sources (upwelling of CO_2-enriched water) and sinks (photosynthetic production of biomass) of CO_2 to the surface ocean and long air/sea equilibration times. High pCO_2 indicates that the equatorial surface ocean acts as a net source of CO_2 to the atmosphere, whereas temperate and most polar surface oceans are either in equilibrium or act as a net sink for CO_2. If the nature of upwelling in the equatorial ocean were to change, this delicate balance would be altered, thus changing the net flux of CO_2 to the atmosphere and causing perturbations in atmospheric pCO_2 on a time scale of months to years. If the equatorial ocean warms up markedly as a result of reduced upwelling, such as that which occurs during El Nino, opposing effects on the CO_2 balance are expected: (1) the solubility of CO_2 will be lower in warmer water, (2) rates of primary production will be lower as a result of reduced nutrient levels, and (3) excess CO_2 supplied from subsurface waters will

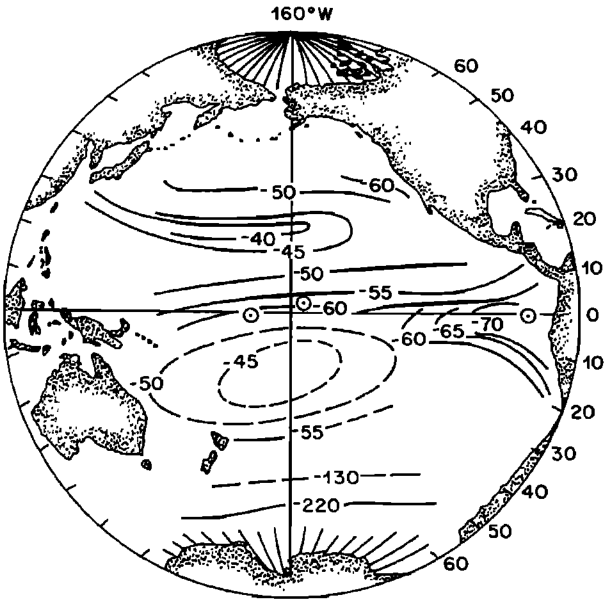

Fig. 1. Isolines of preanthropogenic radiocarbon levels in surface waters of the Pacific Ocean displayed in $\Delta^{14}C$ units (per mil). Distributions are based on early seawater measurements [Rafter and Fergusson, 1957; Rafter, 1968; Bien et al., 1960] and analyses of coral bands [Druffel, 1981a, b; Konishi et al., 1983; Toggweiler, 1983]. Dashed isolines indicate estimates based on post-bomb distributions [Linick, 1975]. Circles show sampling locations for this study.

be reduced due to decreased upwelling. The first two effects will cause an increased release of CO_2 from surface ocean to atmosphere, whereas the latter effect would cause a reduction of the flux of CO_2 into the atmosphere. Equatorial warming, such as that experienced during El Nino, causes the post-bomb $^{14}C/^{12}C$ ratios in surface seawater to rise [Druffel, 1981a, and unpublished manuscript, 1984]. Reduced upwelling increases the residence time of waters at the surface, allowing more of the $^{14}CO_2$ admitted from the atmosphere to be retained within the equatorial zone. On these time scales, however, oceanic $^{14}CO_2/^{12}CO_2$ ratios would still be depleted with respect to that in the atmosphere. This is due to a long isotopic equilibration time for $^{14}CO_2$ of 10-14 years [Druffel and Linick, 1978], in comparison to the chemical equilibration time for CO_2 of only 1 year [Broecker et al., 1980].

El Nino is the response of the ocean and climate to a forcing function that is not yet understood. Wyrtki [1965] determined that a high Southern Oscillation Index (SOI), which is a measure of the strength of the southeast trade winds over the southern Pacific, preceded El Nino by 1 year. McCreary [1976] proposed that subsequent reduction of the SOI generates an eastward propagating equatorial Kelvin wave front, which causes the water accumulated in the western Pacific to "slosh back" toward the eastern Pacific. These El Nino/Southern Oscillation (ENSO) events are associated with a dramatic sea level lowering at Truk Island (7.5°N, 151.9°E) [Meyers, 1982] and considerable thickening of the pycnocline, as well as high sea level and heavy rainfall in the eastern tropical Pacific. The Peru Current is virtually absent during these periods, and upwelling is suppressed to depths well below the mixed layer. As a result, warm, nutrient-poor, low-salinity waters invade the eastern and central tropical Pacific, causing massive deaths of various fishes and guano birds that normally feed on the fish. El Nino is an economic and ecological disaster to the western coast of South America.

Statistics on the periodicities of the SST anomalies associated with ENSO are relatively unknown prior to 1960, as there is no uniform index available in which these anomalies have been recorded. Until recently, researchers have relied on records of water temperature, rainfall, and disturbances to the anchoveta industry, mostly from the coasts of Peru and Ecuador. However, El Nino is not only a coastal phenomenon; in fact, some weak and moderate events occur only at sea and do not extend as far east as the coast [Wyrtki, 1975]. Long-term records from offshore locations, such as the Galapagos or the Line Islands, would provide the index necessary to assess the periodicity of temporal variations of SST in the eastern tropical Pacific. Initial efforts to obtain such a uniform index from stable oxygen isotope ratios in annual coral bands are presented here. These data will be compared to the record of ENSO occurrences reconstructed by Quinn et al. [1978] from a combination of environmental, hydrographic, and meteorological data.

The purpose of this study is threefold: (1) to establish the usefulness of coral skeletons as integrators of SST in the eastern and central tropical Pacific region, (2) to identify a coral-inhabited island that is particularly sensitive to weak as well as strong ENSO events, and (3) to reconstruct an accurate record of past ENSO events, as well as long-term (several year) changes in SST and salinity for the past 50 years.

Corals as Integrators of SST

It is generally believed that hermatypic corals accrete aragonite from an internal pool of carbon and oxygen within the calcioblastic layer according to the following equation:

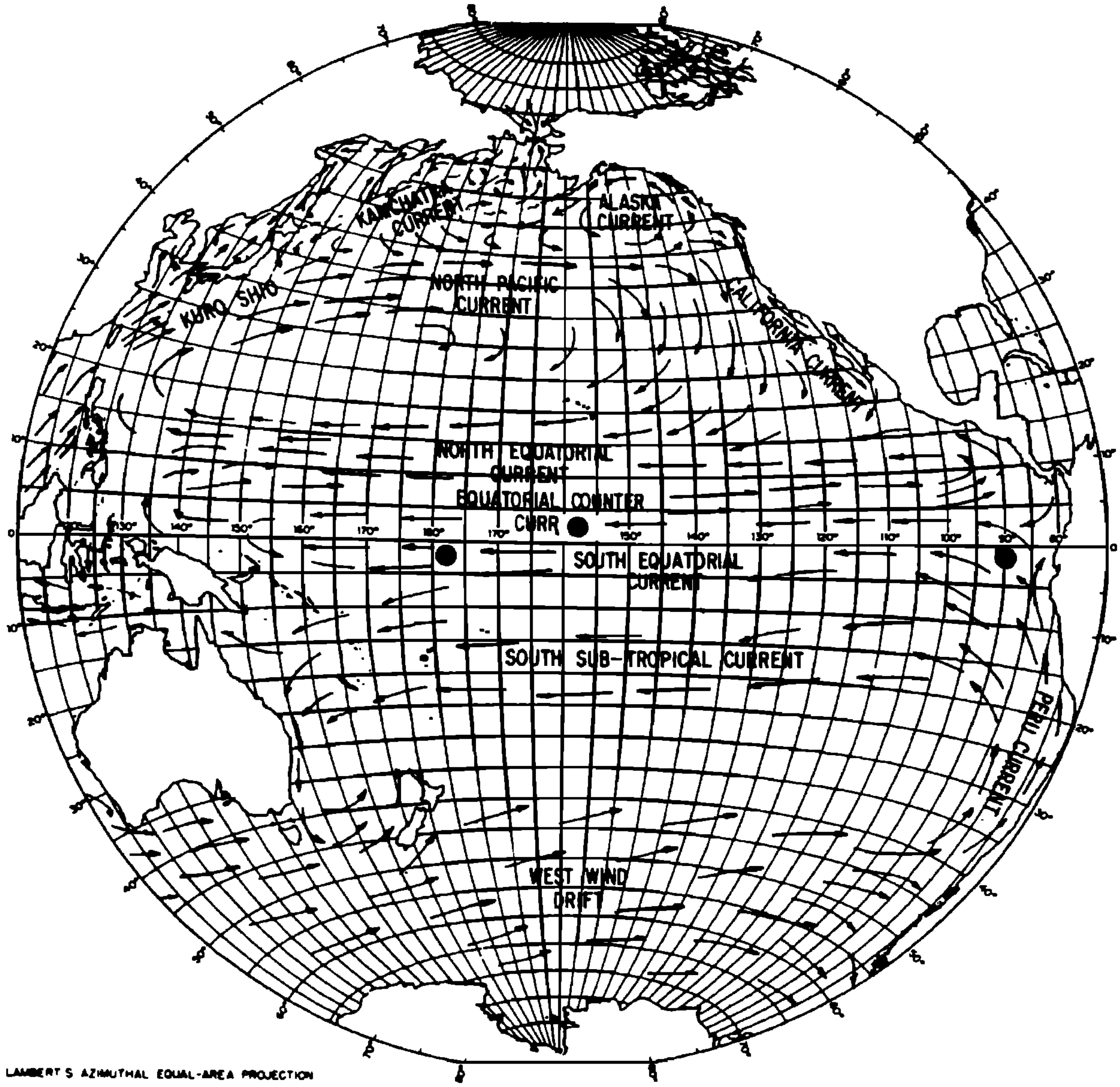

Fig. 2. Surface currents of the Pacific Ocean [from Michel, 1974]. Circles show sampling locations: Canton Island (2°S, 171°W), Fanning Island (4°N, 159°W), and the Galapagos Islands (1°S, 90°W).

$$Ca^{2+} + 2HCO_3^- \rightleftharpoons CaCO_3 + H_2O + CO_2 \qquad (1)$$

Sources and sinks of C and O in this internal pool are controlled by three major processes: (1) input of dissolved inorganic carbon (DIC) and H_2O from surrounding seawater, (2) uptake and release of CO_2 by metabolic processes such as coral respiration and algal photosynthesis, and (3) accretion of aragonite. The effect of metabolic processes on the $^{13}C/^{12}C$ ratio of accreted aragonite appears to be more important than that on the $^{18}O/^{16}O$ skeletal ratios (see Swart [1983] for a review). Metabolic processes contribute toward a constant overall depletion in coral skeletal $\delta^{18}O$ values, with respect to that expected for equilibrium precipitation, however, variations of the $^{18}O/^{16}O$ ratio (in areas of constant salinity and water composition) are controlled by fluctuations of SST [Weber and Woodhead, 1972]. Using high-resolution sampling of Montastrea annularis from three sites in the North Atlantic, Fairbanks and Dodge [1979] obtained a direct correlation between $\delta^{18}O$ measurements and month-

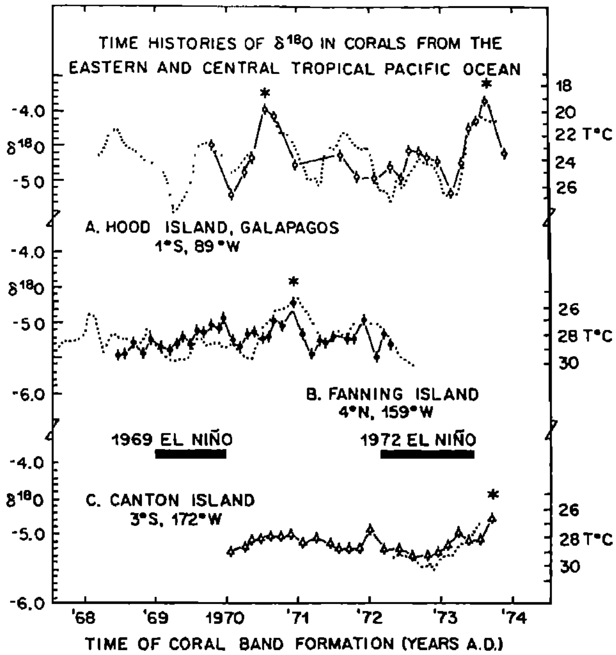

Fig. 3. Time histories of $\delta^{18}O$ in subannual coral samples from the eastern and central tropical Pacific Ocean during the period 1968–1974. Sea surface temperature for each location is shown by the dotted lines. The SST record plotted for Fanning is from Christmas Island (2°N, 157°W). Notice that the amplitude of the seasonal signal, as well as that of the 1972 El Nino, is lower as distance from the eastern tropical Pacific (Galapagos Islands) increases. One out of nine results represents an average of duplicate $\delta^{18}O$ analyses. An asterisk marks unusually cool periods following El Nino/ Southern Oscillation events (see text for detail).

ly averages of water temperature at each site. Similar results were obtained for Porites from the northern Great Barrier Reef [Chivas et al., 1983], and for Pocillopora damicornis from Oahu [Weil et al., 1981) and from the Gulf of Panama [Dunbar and Wellington, 1981].

These studies revealed that $\delta^{18}O$ is shifted by +0.21–0.23°/oo for every 1.0°C drop in temperature, the same as that observed by Epstein et al. [1953] for the inorganic precipitation of calcite. In this way, changes of <0.5°C are easily detected. Some authors have obtained conflicting results, due to additional variables that affect the $\delta^{18}O$ signature, such as salinity changes due to high rates of evaporation and precipitation in surrounding seawater [Swart and Coleman, 1980]. A shift of +0.06°/oo in $\delta^{18}O$ is encountered for every 0.10°/oo rise in salinity. Thus, the $\delta^{18}O$ variation in coralline aragonite is a combined signal reflective of changes in SST, salinity, and water composition. At the open ocean sites in the central tropical Pacific, it is estimated that most of the $\delta^{18}O$ signal is due to temperature changes and a minimal amount to changes in salinity [Love, 1971–75].

Study Sites

Two species of massive corals were collected from five sites in the tropical Pacific (Figure 2). Heads of Porites lobata were taken from the leeward (CTFN) and windward (CFAN) sides of Fanning Island (3°52'N, 159°15'W) and from Canton Island (2°48'S, 171°43'W). Pavona clavus was gathered in the Galapagos Islands from Urvina Bay (0°25'S, 91°17'W) and Hood Island (1°23'S, 89°37'W). All corals were collected from <10 m depth in outer reef locations and were laved by open ocean waters. Lagoons or areas influenced by lagoonal or coastal runoff were avoided so that temperature records representative of open ocean water masses could be obtained.

The study sites lie in the path of the westward flowing South Equatorial Current (SEC) system, which is supplied mainly by the Peru Current (Figure 2). Upwelling is influenced by the action of the southeast trade winds on the equatorial surface waters, and is especially intense during the months of May through November [Wooster and Guillen, 1974]. Strong SE trades also cause coastal upwelling off South America and at the same time power the Peru Current system. As a result of the extensive upwelling in the central and eastern tropical Pacific, surface waters are typically cool, saline, nutrient-rich, and have high pCO_2 levels.

Methods

Whole coral heads were collected and air dried and then cut with a diamond-edged rock saw along the axis of growth. X-radiographs of slabs 5–10 mm thick revealed regular variations in skeletal density. Alizarin staining techniques, long-term field observations [Glynn and Wellington, 1983], bomb-radiocarbon distributions [Druffel, 1981a, and unpublished manuscript, 1984] and stable oxygen isotope studies (this work) revealed that Pavona from the Galapagos accreted one band pair per year of high- and low-density aragonite. In contrast, most Porites coral from the Fanning and Canton sites accreted two density band pairs per year, probably the result of reduced seasonal variation in some parameters controlling coral growth (SST, ambient light, etc.). An exception was the Porites head collected by J. R. Toggweiler from the NW coast of Fanning Island (CTFN) which had only one band pair per year.

The Galapagos specimens were sectioned into annual bands; radiocarbon measurements were re-

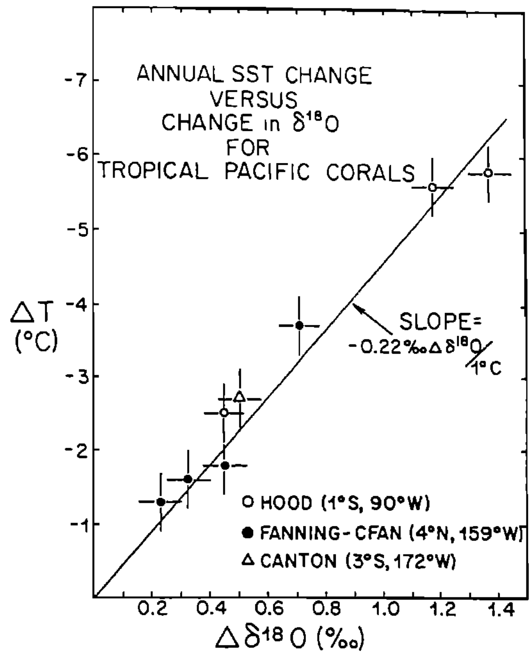

Fig. 4. Correlation between annual range in historical sea surface temperature (SST) records (ΔT°C) and annual range in $\delta^{18}O$ values ($\Delta\delta^{18}O$) in coral bands from Hood Island (Galapagos Islands), Fanning Island, and Canton Island. The line shown represents a slope of 0.22°/oo per 1°C decrease in SST predicted by the temperature-dependent aragonite-water fractionation factor. This slope is the same as that defined for the equilibrium precipitation of calcite [Epstein et al., 1953].

ported previously [Druffel, 1981a]. Small aliquots of material used for ^{14}C measurements were saved and analyzed for stable oxygen and carbon isotopes. Subannual samples were drilled (1 mm diameter) from Fanning, Canton, and Hood Island coral slabs. As the upward growth rates of these corals were not the same, sampling resolution varied among specimens. A growth rate of ~1.5-2.0 cm/yr for Fanning (CFAN), Canton, and Hood Island heads allowed sampling of 9-12 samples/yr whereas the second Fanning specimen (CTFN) grew less than 1.0 cm/yr, which reduced the sampling resolution to 6 samples/yr.

In preparation for stable isotope analyses, samples were crushed in methanol and roasted at 375°C under vacuum for 1 hour. They were acidified with 100% orthophosphoric acid at 50°C, and the evolved CO_2 was measured on a V.G. Micromass 602E mass spectrometer. Results are reported in the standard δ (per mil) notation relative to the PDB-1 Chicago Standard, assuming $\delta^{18}O$ (NBS-20) = -4.18°/oo and $\delta^{13}C$ (NBS-20) = -1.06°/oo. The precision of $\delta^{18}O$ measurements determined from numerous duplicate analyses of the same aragonite is $\pm$0.07 °/oo standard deviation (SD).

The $\delta^{13}C$ signal in corals is sufficiently complicated, and the controls on it are so numerous, that adequate treatment of the $\delta^{13}C$ data collected as part of this study is not possible in this brief a forum. These data, as well as the radiocarbon measurements of the mid-Pacific corals, are discussed in a separate paper [E. M. Druffel, unpublished manuscript, 1984].

Intrannual $\delta^{18}O$ Results: Central and Eastern Tropical Pacific

Stable oxygen isotope analyses of subannual coral samples that grew from 1968-1974 in the tropical Pacific are shown in Figure 3. The chronology of each isotope curve was established by fitting the $\delta^{18}O$ measurements to records of average monthly SST from each location (dotted lines). Temperature records from Christmas Island (2°N, 157°W) are plotted with the Fanning data (4°N, 159°W), as no records from Fanning were available for this time period. The temperature axis (right side of Figure 3) is scaled relative to $\delta^{18}O$ (left side of Figure 3), assuming that temperature alone affects $\delta^{18}O$ (-0.22°/oo per 1°C rise). Despite the use of different species in this study, $\delta^{18}O$ values from Hood Island are proportionately greater (by 0.8°/oo, 4°C cooler) than those from the warmer locations in the central tropical Pacific.

At all three locations, temperature appears to be the predominant factor controlling the variations of the $\delta^{18}O$ signal. In Figure 4, the annual range in SST (ΔT) during each year is plotted versus the observed annual variation in $\delta^{18}O$ ($\Delta\delta^{18}O$) at each site. There is close agreement between these values and the line representing a direct correlation between SST and $\Delta\delta^{18}O$ (slope is 0.22°/oo per 1°C). From this agreement, it appears that changes in salinity that occurred at these tropical locations were either small (<0.3°/oo) or short-lived.

Even during the ENSO periods of 1969 and 1972, reductions in salinity are not apparent in the $\delta^{18}O$ records. We observe no large negative excursions of $\delta^{18}O$ beyond those predicted by the observed temperature changes. It appears, however, that despite the good correlation between annual ΔT and $\Delta\delta^{18}O$ in the Fanning record, there is a discrepancy between absolute $\delta^{18}O$ values and SST. Values of $\delta^{18}O$ seem too high during most of 1969 and low during most of 1970. The SST record used for comparison, however, was taken from Christmas Island, which is located 2° closer to the equator (2°N, 157°W) than Fanning Island (4°N, 159°W) and is influenced by different water masses during part of the year.

It might be expected that differences in salinity accompany ENSO events in the vicinity of the Galapagos Islands, due to the influx of fresher waters from the Panama Basin [Wyrtki et

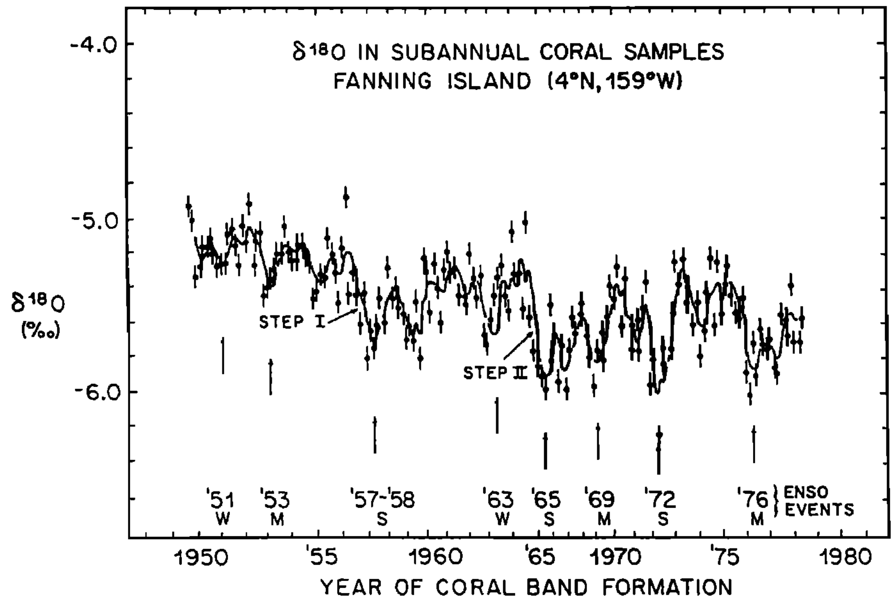

Fig. 5. Time history of $\delta^{18}O$ in subannual coral samples from a specimen collected from the leeward side of Fanning Island (CTFN). The line is a 6-month (3 point) running mean of the values. Note the two-step trend toward lighter values for 1957 (step I) and 1965 (step II). Correlation of low $\delta^{18}O$ values with ENSO events is consistent throughout the record, with the strong event of 1972 being the most impressive. The severity of each ENSO event is indicated by (W) for weak, (M) for moderate, and (S) for strong. Results of duplicate analyses are plotted as a single averaged point.

al., 1976]. However, there is no evidence of this effect during the 1972 El Nino at Hood Island, as $\delta^{18}O$ changed in proportion to the observed average temperature rise for this period (Figure 3). Hood is the southernmost island in the Galapagos archipelago, apparently far enough south to escape the influence of low salinity waters accompanying El Nino.

A prominent feature in each of the three stable isotope records is the appearance of pulses of cool water (high $\delta^{18}O$ values) with the return of upwelling after ENSO events. These pulses are noticed during mid-1970 and mid-1973 at Hood, late 1970 at Fanning, and late 1973 at Canton (marked by asterisks in Figure 3). Occurrence of cool water pulses is in phase with high pCO_2 anomalies found by Bacastow et al. [1980] at several of the CO_2 monitoring sites in the Pacific. This suggests that the renewal of upwelling following an ENSO event is related to the net flux of CO_2 into the atmosphere.

Thirty-Year Subannual $\delta^{18}O$ Record at Fanning Island

Stable oxygen isotope results are reported for the second Fanning coral, CTFN, sampled subannually (6 samples/yr) over the period 1950-1979 (Figure 5). A 6-month (3 point) running mean is plotted as the solid curve. It is important to point out that $\delta^{18}O$ results from the two Fanning corals are similar, with the exception of a $1\frac{1}{2}$-year period when there was a 0.2°/oo offset (1969-1970) (Figures 3 and 5). The reason for this may be the fact that CTFN grew off the leeward (NW) side of the island, which would be influenced by slightly warmer waters, especially during ENSO events (i.e., 1969), than those at the windward (SE) edge, where CFAN was collected.

An annual temperature signal is discernable during most years in the CTFN results. However, its amplitude appears attenuated by about a factor of 2 during the 1950's. This is due to the fact that the coral slab deviated from the vertical axis of growth during this period, causing contamination in the drilled samples due to incorporation of earlier and subsequently accreted material.

However, this does not account for the overall greater values apparent during the earlier part of the record. A least squares fit of the data for non-ENSO periods reveals an overall decline of 0.45°/oo from 1950 to 1979. In particular, two periods of rapid decline in $\delta^{18}O$ (steps I and II in Figure 5) appear during the onset of two strong ENSO events (1957 and

1965), after which there is a partial recovery toward higher values. If this $\delta^{18}O$ record is representative of the area surrounding Fanning Island, sudden changes in the combined SST/salinity signal are indicated and appear to be induced by major ENSO events. The trends apparent in the 30-year Fanning Island record do not appear to correlate with the surface air temperatures reported by Angell and Korshover [1983] for the tropics, most likely because the sites from which air temperature data were chosen were remote with respect to the eastern and central tropical Pacific Ocean. It is difficult to ascertain the significance of high $\delta^{18}O$ values (indicative of lower SST) during 1963-1965, due to the scatter. There is evidence in the literature of slower growth rate of pCO_2 in the atmosphere [Bacastow, 1979] and lower world air temperatures [Angell and Korshover, 1983] during the period following the Agung eruption in 1963.

Superimposed on the long-term changes are the presence of strong (1957, 1965, 1972), moderate (1953, 1969, 1976), and weak (1951, 1963) ENSO events marked by unusually low $\delta^{18}O$ values. There are also lower $\delta^{18}O$ values during 1959 and 1974, presently considered non-ENSO periods. The average offset during strong events is about 0.3°/oo, which reflects a maximum of 1.5°C warmer SST (assuming no salinity change) averaged over 12-month periods. The severe event of 1972 stands out among the other strong ENSO episodes because of the very low $\delta^{18}O$ value of -6.25°/oo revealed at the height of the event. Moderate and weak events are marked by a decrease of 0.1-0.2°/oo and are somewhat proportional to the length of each event, which ranges from 4 to 10 months.

Interannual $\delta^{18}O$ Results: Eastern Tropical Pacific

Results of *Pavona clavus* samples from Urvina Bay (UB), Isabella Island and from Hood Island (HI) are presented in Figure 6. An overall enrichment of ^{18}O by 0.3°/oo is apparent in the UB results relative to those for HI, due to the enhanced influence of Ekman divergence and/or the Cromwell Current at this location nearer the equator (0°25'S). The UB results average -4.08°/oo during the 1930's and -3.96°/oo during the 1940's, with the exception of a few low values that represent coral growth during ENSO events. The major event of 1941 is displayed by a reduction in $\delta^{18}O$ of ~0.33°/oo. The moderate (1939-1940 and 1953) and weak (1932, 1943-1944, and 1951) events described by Quinn et al. [1978] show a smaller reduction (0.10-0.20°/oo). Overall, there is agreement between the historical record compiled by Quinn et al. [1978) and the $\delta^{18}O$ record from banded corals. This correlation supports the suspicion that the low $\delta^{18}O$ values obtained for coral growth during 1937 and 1952 also represent warm water/low salinity conditions in the eastern tropical Pacific that have not previously been recognized as such in the literature. These values are significantly depleted (by 0.15-0.20°/oo) with respect to the baseline values established for the 1930's and 1940's. Evidence that the weak ENSO event of 1951 lasted through 1952 is provided by the sea level atmospheric pressure anomaly between Santiago, Chile, and Darwin, Australia [Quinn et al., 1978], which lasted throughout the first half of 1952. There was no similar SOI anomaly apparent during 1937. Nonetheless, the lower $\delta^{18}O$ value indicates the presence of higher SST or lower-salinity waters, or a combination of both, during 1937. This suggests that a weak ENSO event, not associated with an SOI anomaly, may have occurred several hundred kilometers west of the South American coast, and thus went unnoticed in the historical records. The high value for 1950 growth (-3.87°/oo) indicates an unusually cold period, which agrees with records of SST along the Peruvian coast.

Most important is the long-term trend toward lower $\delta^{18}O$ values apparent in the 1930's (Figure 6), which is evidence of higher SST and/or less saline waters for this period. A least squares fit of the data from non-ENSO years reveals a significant decrease from -4.01 in 1930 to -4.14°/oo by 1938 (Figure 6). Least squares analyses of the 1940's data indicate an insignificant slope, with values that range from -4.01°/oo in 1942 to -3.92°/oo by 1950. The average offset of $\delta^{18}O$ values between the 1930's and 1940's, therefore, is 0.10-0.15°/oo, which is equivalent to the signal from a weak ENSO event. Whether the 1930's was a period of consecutive weak ENSO events or local or widespread warming cannot be absolutely determined at this point. This area was tectonically active, which led to the death of the reef in 1954 when a portion of the shoreline was uplifted [Richards, 1957]. However, there is no evidence of warm water inputs from lava pools or other tectonically associated water bodies [P. Glynn, personal communication, 1980]. In view of this and the exposed location of Urvina Bay to equatorial currents (i.e., Cromwell Current), it is likely that this coral was accurately recording a widespread warming event (or a reduction in the countercurrent flow) in the eastern tropical Pacific during the 1930's.

El Nino events recorded by Hood Island coral during 1965, 1969 and 1972 displayed roughly the same depletion in ^{18}O (0.2-0.5°/oo) as that observed in the UB sample. It is important to note that results of annual sampling of the 1972 event (-4.85°/oo) agree with the results obtained from subannual sampling (Figure 3) where the values ranged from -4.6 to -5.0°/oo

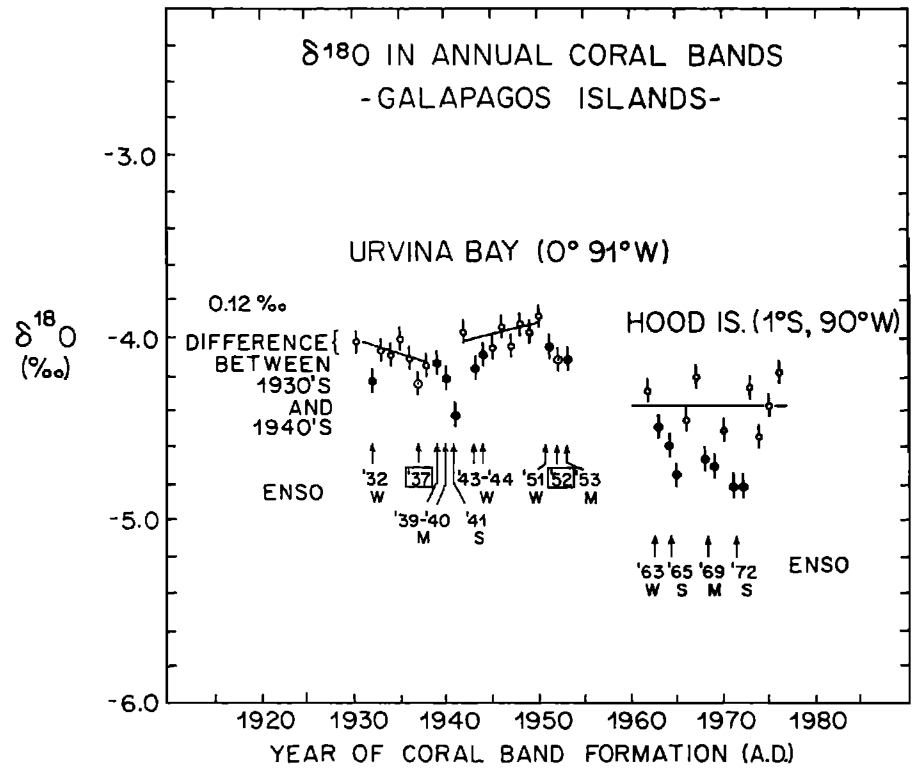

Fig. 6. Stable isotope measurements in annual samples from corals collected in the Galapagos Islands. Each point represents an average of two to four analyses. During El Nino years (solid circles), $\delta^{18}O$ is lower, indicating the presence of warmer and/or less saline waters. Lower $\delta^{18}O$ values are also obtained for 1937 and 1952 (open circles with dot), periods which are not considered ENSO events in the literature. Values from non-ENSO years (open circles) are lower during the 1930's than during the 1940's, suggestive of overall warmer sea surface temperature during the earlier period (see text for details).

with an average of -4.8°/oo. The baselines obtained using both sampling procedures for normal years are also similar (-4.3 to -4.5°/oo).

Unlike the UB record, values from the years preceding ENSO events (1964, 1968, and 1971) in the Hood Island record are also depleted in ^{18}O. This is probably a function of the sectioning procedure which splits a given El Nino year (December-November) into two separate annual bands which are from March-February. Thus, 30% of the El Nino signal (December-February) should appear in the preceding year. This suggests that the $\delta^{18}O$ signal associated with ENSO events is stronger at Hood Island than at Urvina Bay. Sectioning of the HI samples was more accurate than for the UB samples, due to the very high growth rate (1-2 cm/yr) and the well-defined annual density bands. In view of this difference, no viable conclusions can be made regarding the suspected trend toward longer El Nino events from the 1930's-1940's to the 1960's-1970's.

The level of noise in the $\delta^{18}O$ values surrounding the HI baseline (-4.35±0.13°/oo SD) is significantly higher than that surrounding the UB baseline (-3.97±0.06°/oo SD, after removing the 0.12°/oo depletion during the 1930's) (see Figure 6). It is difficult to use the CTFN data to test for this change in noise level, as the results from the 1950's are attenuated due to a sampling artifact. A larger noise level in the HI $\delta^{18}O$ results may indicate that occurrences of weak ENSO events had become more frequent during the 1960s and 1970s, or that site HI is more sensitive to weak El Nino events than site UB. However, without $\delta^{18}O$ records from the same time periods for both sites, we cannot distinguish between these two possibilities as explanations of the apparently higher levels of noise.

Discussion

This study has revealed a direct correlation between $\delta^{18}O$ in banded corals and historical records of SST in the extensive region affected by ENSO. There appears to be no noticeable dependence of $\delta^{18}O$ on salinity changes that may have occurred. This provides a valuable integrator of the ocean's response to atmospheric forcing, records that have been incomplete up to this point.

The largest differential between annually averaged $\delta^{18}O$ for normal years and that for ENSO years was found at the two Galapagos Island sites (0.2-0.5°/oo). The amplitude of this signal at the three mid-Pacific sites was about half the size (0.1-0.3°/oo). It is desirable to obtain records from both general locations, however, in order to determine the spatial extent of each ENSO event as well as the temporal relationship between changes in the eastern and central equatorial Pacific. Christmas Island may be a better mid-Pacific location than Fanning, in that there is less influence from currents other than the SEC (i.e., North Equatorial Countercurrent, NECC), which is the predominant current flowing through the region affected by ENSO. Canton Island seems to be located at the westernmost edge of "El Nino country"; however, it will be very important to study the effect that the catastrophic event of 1982-1983 had at this location. If Canton is indeed sensitive only to very intense events, records from this site will be important for corroborating records of these events from more sensitive locations to the east.

It is desirable to use monthly sampling intervals from coral bands to determine accurately the severity and length of individual ENSO events. However, this involves an enormous number of analyses. Also, the data may not represent monthly averaged SST values if the upward growth rate of the coral is less than 1 cm/yr. Calcification takes place on the calcioblastic layer surrounding the individual cup-shaped polyps, which extend down into the skeleton. Thus calcification occurs simultaneously over a distance equal to the depth of polyp (1-5 mm). Should corals with high growth rate and small polyp size not be available from a given location, $\delta^{18}O$ from seasonal samples would at least allow us to distinguish between weak and strong ENSO events.

There is evidence from the Urvina Bay $\delta^{18}O$ record that ENSO conditions prevailed during 1937 and 1952, despite the absence of these events in historical records from the South American coast. This incongruity suggests that records from the South American coast are not necessarily indicative of warming events in the eastern tropical Pacific. Isotopic records from a location off the coast may be a better integrator of the incidence of ENSO. A revised time history of ENSO events based on these UB data appears in Figure 6. The reliability of the record can be improved by obtaining higher precision ($\pm$0.03°/oo) and by implementing more careful sampling procedures on a high growth rate coral that exhibits minimal intra-annual banding.

A major conclusion of this study is that there appears to have been decade time scale variability of SST in the eastern and central tropical Pacific over the past half century. Warmer (and/or less saline) waters, by about 0.5°-1°C, apparently predominated in the Galapagos Islands during the 1930's than during the subsequent decade. In addition, sea surface temperature appears to have increased by about 1°-2°C from 1956 to 1965 at the Fanning Island site. If these changes are representative of large-scale warmings over a substantial area of the tropical Pacific, significant effects on the short-term CO_2 cycle are likely.

Bacastow [1976] observed decreased pCO_2 at the south pole and at Mauna Loa during strong SOI and increased levels when the winds relaxed, marking the onset of an ENSO. More recently, he has extended this correlation to include ocean station PAPA (50°N, 145°W) and Fanning Island [Bacastow et al., 1980]. Schnell et al. [1981] calculated an exchange factor of 0.64 ± 0.07 ppm atmospheric CO_2 per 1°C change in SST for two sites in the North Pacific. From these studies, it was shown that atmospheric CO_2 was stored in cooler than normal surface waters and that when SST was higher than normal, there was a net flux of CO_2 to the atmosphere. However, maximum pCO_2 levels are not reached until the year following an ENSO event [Bacastow et al., 1980], which is coincident with the renewal of upwelling and the appearance of unusually cool waters in the tropical Pacific (Figure 3). Newell et al. [1978] demonstrated that the SST changes in the Pacific equatorial upwelling region are correlated with these CO_2 changes, with the Indian and Atlantic oceans contributing only minor fractions to the variance. Gammon et al. [1984] described a slower than normal rise in atmospheric CO_2 during the first part of the severe ENSO of 1982-1983 and a subsequent net release of about 3 Gt C from the surface ocean to the atmosphere during the warmer second year.

Bacastow et al. [1980] used a simple equilibrium model to calculate that a change in SST representative of a major ENSO event would correspond to an atmospheric CO_2 rise of only 0.4 ppm, approximately 40% of the observed change. However, it is difficult to understand how a rise in SST could cause a higher rate of CO_2 flux into the atmosphere, as cool upwelling waters of the SEC/Peru Current regime have very high pCO_2 values [Keeling et al., 1965] and are believed to be a net source of CO_2 to the atmosphere during non-ENSO conditions. Decreased upwelling might be expected to reduce pCO_2 in ocean water and as a result reduce the net flux of CO_2 to the atmosphere. On the other hand, increased primary production during upwelling (cold) periods may act to decrease pCO_2 in surface waters and thus reduce their capacity as a CO_2 source to the atmosphere, in contrast to nonupwelling periods when nutrients are low.

Nonetheless, the net flux of CO_2 from ocean to atmosphere occurs during the latter part of an ENSO event and during the following 6-12 month period. This suggests that the appearance of warm waters associated with ENSO, as well as the return of cool, CO_2-rich upwelling waters to the surface, both contribute to a higher net flux of CO_2 from ocean to atmosphere.

When we consider the decade time scale variability of SST revealed by corals, the impact on the carbon cycle will most likely be even greater. The decade-long perturbation in SST noticed during the 1930s at the Urvina Bay site was approximately 0.5°-1°C. This SST anomaly is about half of the perturbation noticed during a major ENSO event (Figure 6). If the impact on the carbon cycle during a 12-18 month ENSO event is taken as a net addition of 2-3 Gt C from surface ocean to atmosphere during the second part of the event, and the 0.5°-1°C rise at the Galapagos is symptomatic of a widespread warming throughout the equatorial Pacific, then it is estimated that there was a net flux of 1-2 Gt C from surface ocean to atmosphere during the early 1930's, in addition to the net release of 4-6 Gt C during the ENSO events of 1932, 1939-1940, and 1941. It is likely that most of the net CO_2 input from sea to air as a result of the long-term warming was restricted to the early 1930's after which quasi-steady state conditions were attained despite the retention of high SST. However, if the CO_2 release was dominated by the failure of the marine biota to resume a high level of biomass production in the equatorial zone, then net CO_2 release to the atmosphere over the entire interval of high SST would be possible. Had the oceans continued to supply net CO_2 over the entire period, a measurable effect would be expected in the $\delta^{13}C$ record from tree rings.

Similarly, the two-step warming indicated by the Fanning Island (4°N, 159°W) record from 1956 to 1970 may have caused a net input of carbon to the atmosphere. It is difficult to quantitatively assess the spatial extent of this SST anomaly, however, because of its location; it may reflect temperature changes in the NECC rather than in the SEC. An indication of this is borne out by the temperature records from Christmas Island, which do not indicate a warming over this time period. In the event that these data represent a widespread warming, an upper limit for the net input of CO_2 from surface ocean to atmosphere during this 1°-2°C warming is estimated to be 2 Gt C during the late 1950's (step I) and 1 Gt C during the mid-1960's (step II). This correlates with the overall increase in pCO_2 (corrected for fossil fuel addition and seasonal variation) of ~1 ppm seen in the record from the south pole [Keeling, 1973] during these periods.

Conclusions

The major purpose of this study was to corroborate the usefulness of coral bands as integrators of SST in the tropical Pacific and subsequently to reveal the presence or absence of ENSO episodes prior to the time for which good historical SST records are available.

Major conclusions of this tropical Pacific study are as follows:

1. The $^{18}O/^{16}O$ ratios in coralline aragonite from monthly and annually averaged growth increments are directly correlated with historical SST records from the same time periods. Salinity variations appear to have been minimal during the period 1968-1973, even during ENSO events.
2. The $\delta^{18}O$ signal during strong ENSO events is greatest at the Galapagos Island sites (0.45°/oo), less at Fanning Island (0.20-0.30°/oo) and very weak at Canton Island (<0.20°/oo). Therefore, the best location for tracking past ENSO events is the Galapagos Islands. It is anticipated that Christmas Island would be the most desirable mid-Pacific location, due to its position with respect to the SEC.
3. Decade time scale variations of SST were noticed in the tropical Pacific: (1) the eastern tropical Pacific was warmer by ~0.5°-1°C during the 1930's than during the subsequent decade, and (2) the mid-tropical Pacific underwent a warming trend from 1956 to 1970, which occurred rapidly in two stages coincident with the two major ENSO episodes of 1957 and 1965. The onset of each of these warming periods most likely accompanied increases in the net input of CO_2 from surface ocean to atmosphere of 1-3 Gt C.

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