Various Studies Using ^{18}O Distribution within Paleoclimatic Proxy of Past El Niño/Southern Oscillation Disturbances

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ABSTRACT

El Niño/Southern Oscillation (ENSO) is an excellent example of the interaction between the ocean and the atmosphere and their combined effect on climate. The need for reliable global records of high-resolution paleoclimatic data has become invaluable for ENSO experts attempting to develop a means for prediction. Isotopic records from tropical rainfalls, fossilized marine foraminifera, skeletons of long-lived corals, and ice-cores of tropical ice fields have provided scientists a means by which the length of the climate record can be extended beyond the short period of observed coverage. If these climatic indicators do indeed provide an accurate reconstruction of climatic conditions within the regions directly affected by ENSO-related events, then perhaps the same techniques can be used to interpret teleconnections related to ENSO disturbances.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The present understanding of the El Niño/Southern Oscillation (ENSO) has changed rather quickly in the past decade in response to at least two factors. On one hand, the realizations that ENSO-related disruptions are not restricted to the eastern Pacific and rather, often cause many other atmospheric aberrations on a global scale (Fig. 1). Today, these disruptions are referred to as teleconnections. Among these are droughts in Central America, Philippines, Southern India, Indonesia, Africa, and Australia. Large scale brush fires and forest fires -- some on the order of millions of acres -- are associated during these drought periods in Australia and Kalimantan (Borneo). Flooding is more prevalent in the United States, Cuba, Northern Peru, Southern Brazil, Northern Argentina, Eastern Paraguay, Bolivia, and Western Europe. Teleconnections that have been statistically correlated with the ENSO have extensive social impacts such as homeless and poverty stricken individuals, crop failure, and national economies severely disrupted. On the other hand, a large effort has been mounted in the past two decades to identify indicators for past ENSO events. The outcome has provided today's experts with a multitude of proxy for tracking past ENSO events (Fig. 2). One of these tools widely used by multi-disciplinary science teams is to determine the record of oxygen isotopes within ice-cores, corals, and fossilized marine plankton. The oxygen isotope containing eighteen neutrons (^{18}O) is frequently preferred for El Niño studies for two reasons: first, its content ratio is a counterpart of specific chemical conditions of water, and second, its association with carbon molecules enable it to be recorded within living and fossilized organisms.

I will provide an extensive perspective on the nature of links and mechanisms between paleoclimatic records and ^{18}O records. Because it has been found that the ENSO system governs interannual variability throughout the world, it has been suggested that evidence of historic ENSO events and its teleconnections can be determined isotopically on a greater geographic range. An overview of the El Niño/Southern Oscillation phenomenon is followed by a discussion on the properties of oxygen isotopes and means for calibrating and reporting $\delta^{18}O$ values. Finally, I will focus on oxygen isotope tracers that are characteristic of tropical rainwaters, foraminifera, tropical ice-cores, and western and eastern pacific corals. It was necessary to limit the discussion on each section. However, I believe that a comprehensive summary for each of these ENSO-related isotopic signals has been provided.

ENSO: An Overview

The Paita sailors, who in the past century frequently navigated along the west coast of Peru, recognized an abnormal counter-current and named it "El Niño" (Spanish for "the Christ Child") because it had been observed to appear immediately after Christmas (Philander, 1989). For the coastal inhabitants of this region, the Peruvian Current was something that they normally relied upon to supply cold, nutrient and oxygen-rich waters that yielded dense concentrations of marine life. However, on occasion the El Niño would disrupt the productive years with abnormally warm waters that killed off much of the marine life, along with intense rainfalls producing devastating floods within the region (Philander 1989; Enfield 1992; Sarachik 1997). At the turn of this century, despite efforts by scientists to document and determine the climatic anomaly, experts still didn't have a plausible explanation for the driving forces behind El Niño. During the 1920's, a British scientist, named Sir Gilbert Walker recognized rainfall patterns with oceanic temperatures while trying to improve upon failed methods for predicting the vagaries of India's monsoons. After further research, he also noted a connection between barometer readings at weather stations on the eastern and western sides of the Pacific (Tahiti and Darwin, Australia). Walker found that when barometric pressure rises in the east, it usually falls in the west, and vice versa. The rise in the east was referred to as the "high index" phase. It represents the period when the barometric pressure is higher (high-pressure gradient) near and to the east of Tahiti than farther to the west near Darwin. Walker concluded that the east-west pressure difference along the equator caused the surface air to flow westward. He labeled this pressure gradient as the Southern Oscillation (SO) and suggested that it was responsible for the irregular interannual variations of rainfall patterns and wind field waves in both the tropical Pacific and Indian Oceans (Philander 1989). On the other hand, Walker referred to the "low index" phase as representing the period of low-pressure gradient between the eastern and western Pacific that weakens the trade winds. It is Walker's low index phase that accompanies El Niño events (Cole, Shen, Fairbanks, and Moore 1992). Due to the lack of related data and the complex nature of this oceanic/atmospheric interaction, Walker was unable to suggest any further connections; however, he did predict that whatever was causing the disruptions would become clear once wind patterns above ground level were thrown into the equation.

In the late 1960's (50 years later), a Norwegian meteorologist named Jacob Bjerknes supplied the connection that proved Walker's prediction to be right. Bjerknes' publication quickly gained recognition. He provided the first plausible connections between the unusually warm sea-surface temperatures and the weak easterlies and heavy rainfall that accompanies low-index conditions. Bjerknes' discovery led to the recognition that the warm waters of El Niño and the pressure seesaw of Walker's Southern Oscillation are part of the same phenomenon --

now referred to as the El Niño/Southern Oscillation (or ENSO) Phenomenon (Philander 1989; Enfield 1992; Sarachik 1997; Dunbar, Braddock, and Wellington 1996).

Arguably, one of the most important factors of Walker's high and low index phases is their connection with upwelling. During the high index phase, easterly trade winds drag across the ocean surface towards the west Pacific. This process causes much of the upper water layer to accumulate in the western Pacific and forms a deep thermocline (150-200 m), leaving only a shallow water layer and thermocline (30-50 m) in the eastern Pacific (Philander, 1989). The coastal upwelling of cold, nutrient and oxygen-rich waters occurs through the combined process of the formed ocean water pressure gradient and the Eckman pump associated with the Coreolis Effect. As the trade winds push the surface waters westward and perpendicular to the equatorial region, a trough along the west coasts of continents to the east is created by a significant decrease in sea surface elevation. The created sea level pressures (SLP) gradient forces the cold, bottom waters of the middle latitudes upward towards the surface along the equator. As the counter-clockwise wind patterns of the Southern Hemisphere continue to feed the westward surge of surface waters, the Eckman pump process allows the cold bottom waters in to the South American coastline. However, during the warm phase (so named to represent the warm sea surface temperatures (SST) in the eastern Pacific) of ENSO, upwelling of cool waters along the South American coast is suppressed (Cole, Shen, Fairbanks, and Moore, 1992). Mean SST anomalies reach nearly 2°C in the eastern tropical Pacific and decline to the west, eventually reaching ≤ 0.5°C by 180°W longitude (Rasmusson and Carpenter, 1982). This development dramatically increases rainfall amounts over the region of increased SST's.

One noted characteristic for both the high index and low index phases are the regional fluctuations in SST's and rainfall intensities. Therefore, SST's and precipitation are positively linked (Winter, Goenaga, and Maul, 1991). Without a doubt, most ENSO research in the past has been concentrated in the directly affected areas of the equatorial Pacific. However, Bjerknes also proposed that an unusually warm equatorial Pacific Ocean over a large zonal extent would form deviations in SST gradients over large space scales. As a result, reliable global records of high-resolution paleoenvironmental data need to be established to understand and ultimately to predict climate variability in the interannual-to-decade scale (Winter, Goenaga, and Maul, 1991). In the western Pacific, measurements indicate that intense rainfall alters the salinity of the underlying surface ocean by up to 4 parts per mil (Cole, 1992) and that surface water $\delta^{18}O$ varies linearly with salinity (Cole, Fairbanks, and Shen, 1993). The isotopic variations are a result of distillation associated with the progressive condensation of vapor during deep convection. These isotopic changes provide the means by which past migrations of the ENSO events can be traced beyond the historical record with the use of high-resolution $\delta^{18}O$ records (Cole, 1992; Cole, 1990; Cole, Shen, Fairbanks, and Shen, 1992). The chief purpose of studying $\delta^{18}O$ values is as a means of investigating the processes which in nature separate isotopes on the basis of their mass rather than on the basis of their chemistry. This is known as isotopic fractionation (Craig, 1961; Harmon, 1961; Rollison, 1993). Recent studies have shown that negative $\delta^{18}O$ values related to ENSO conditions (fluctuations in SST's and rainfall intensities) are recorded in tropical rainwater, marine organisms such as foraminifera and diatom silica, tropical ice-cores, and in tropical corals ranging from the western Pacific to the Caribbean (Bird, 1988; Cole, Shen, Fairbanks, and Moore, 1992; Cole, Fairbanks, and Shen, 1993; Dunbar, Braddock, and Wellington, 1996; Juillet, Labeyrie, and Schrader, 1983; Thompson, Mosley-Thompson, and Thompson, 1992; Wefer, Dunbar, and Suess, 1983; Winter, Goenaga, and Maul, 1991). Each of these paleoclimatic proxies has been extensively studied. Each have been found to contribute information on specific ENSO-related conditions, such as SST's, precipitation anomalies, and upwelling conditions that cover a larger geographic record for ENSO. Although there are many other widely used paleoclimatic proxy that provide high-resolution records for ENSO, the remaining sections will focus on the above mentioned proxies after a short discussion on methods for determining $\delta^{18}O$ values in nature.

Methods for Determining δ18O Values

The isotopes of oxygen are attractive as paleoclimatic indicators because they are part of the water molecule. The most important isotopic components of water are H_2O^{16}, HDO^{16}, and H_2O^{18} (Craig, 1961) where the stable isotope ^{18}O makes up about 0.2% of the water molecule. (HDO16 = "heavy water" (deuterium), Friedman et al., 1964.) The oxygen isotopic content of a sample is expressed as the relative deviation of the isotopic ratio $^{18}O/^{16}O$ in the sample relative to that in Standard Means Ocean Water (SMOW). The values are usually expressed as per mil $(^{0}/_{00})$, and the analytical accuracy of the measurement is about 0.1% (Craig, 1961; Jenkins, 1994). The isotope ratio is expressed as δ ('del') value and is calculated as follows:

$$\delta^{18}O\ (‰) = [(^{18}O/^{16}O)\ \text{sample}/(^{18}O/^{16}O)\ \text{standard} - 1] \times 1000.$$

Therefore, a $\delta^{18}O$ value of -8 means that the sample is depleted in ^{18}O relative to SMOW by 8 parts in a million (Rollison, 1993). In precipitation, the contents of ^{18}O and ^{2}H are highly correlated, and a linear regression of ^{18}O and ^{2}H for a given area define a consistent relation, called the meteoric water line (Craig, 1961):

$$\delta^{2}H = 8 \times \delta^{18}O + 10\ (‰)$$

As long as the precipitated water has not been subject to enrichment by evaporation -- such as waters from closed basins (Craig, 1961) -- the ^{18}O of a sample will fall on this line. Because elemental oxygen consists of more than one stable isotope, it is common for each isotope to be fractionated through physical processes as a consequence of the mass difference between the isotopes (Rollison, 1993). ENSO events consist of many physio-chemical processes such as high rates of evaporation and condensation that work as modes of isotopic fractionation for oxygen. Therefore, it is vital to understand the physical and chemical controls on stable isotope fractionation to ensure a correct interpretation of measured ^{18}O ratios. This knowledge will provide the ability to use $\delta^{18}O$ values in the identification of paleoclimatic conditions. For example, temperature is one chief control on oxygen isotope fractionation (Fig. 3; Rollison, 1993), which could be used for calculating SST's. Moreover, it has been suggested that enrichment of ^{18}O in calcium carbonate relative to seawater was temperature-dependant and could be used to determine the temperature of ancient ocean waters (Urey, 1947). A particular method favored by many experts to ensure that their $\delta^{18}O$ data is being correctly interpreted is through the use of models. One model pertaining to the physio-chemical processes involved with isotopic fractionation in precipitation is known as a Rayleigh model (Dansgaard, 1964). This model has proven to useful because it considers the isotopic fractionation to be occurring in an isolated air parcel traveling from an oceanic source towards a polar region. The condensed phase is assumed to form in isotopic equilibrium with the surrounding vapor and to precipitate immediately from the parcel. Under these assumptions, the isotope content of this precipitation is a unique function of the initial isotope mass and water vapor mass within the air parcel and of the water vapor mass remaining when the precipitation forms. This model has proven to be quite accurate in explaining the main features of the global distribution of marked fractionation of $\delta^{18}O$ values in precipitation and ice, along with the observed relationships with local temperatures or precipitation amount and the strong link with $\delta^{18}O$ (Craig, 1961; Dansgaard, 1964, Friedman *et* *al*, 1964; Rollison, 1993). Overall, simple Rayleigh-type models are useful because they help in the understanding of how $\delta^{18}O$ is distributed in precipitation and how it is influenced by the precipitation site and evaporative source temperatures. All of these parameters are the basis for linking the following paleoclimatic proxies to ENSO and its teleconnections.

$\delta^{18}O$ Distribution within Paleoclimatic Proxy

The idea that oxygen isotopes may be useful as a proxy indicator for ENSO-related precipitation and SST is supported by negative $\delta^{18}O$ records -- that can be correlated with historical proxy of ENSO events (Enfield, 1992) -- found in certain marine life and tropical ice sheets. SST by itself is not terribly useful, but in the tropics, once the SST is known, the state of the atmosphere is known to a high degree of approximation (Sarachik, 1997). The common thread between both the living and non-living proxies is the distribution of $\delta^{18}O$ in precipitation which provides the essential SST record (and therefore atmospheric conditions) for areas exposed to ENSO disruptions.

Isotopically Depleted Rainwaters.--Temperatures in the cold eastern Pacific tongue range from 22-27°C, generally well below the temperature of 28°C needed to produce tropical convection and heavy rainfall (NOAA, 1998). However, the warm oceanic waters that are associated with El Niño events are capable of producing very intense oceanic and inland storms in normally arid regions (Turner and Yang, 1993). The global distributions of $\delta^{18}O$ in modern precipitation are well documented through the IAEA network (IAEA, 1981). In order to use an oxygen isotope signal as a paleothermometer (SST), correlation between these concentrations and certain climatic variables have to be established (Craig, 1961; Dansgaard, 1964). One example, is that in the tropics, $\delta^{18}O$ values decrease with increasing precipitation amount (Jouzel, 1996) which, as mentioned earlier, suggests higher SST's. Naturally, with this understanding, it has been recently suggested that meteoric waters associated with ENSO events show a depletion in ^{18}O values (Bird, 1988). Samples collected at two central Pacific stations during a period covering two modern ENSO disturbances reveal a variation of $\delta^{18}O$ in meteoric waters. This variation is a change from "normal" $\delta^{18}O$ values of +2 to -3 $^{0}/_{00.}$ The $\delta^{18}O_{mw}$ (mw = meteoric water) values typically vary from about -2 $^{0}/_{00}$ versus SMOW near the equator (Bird, 1988).

Fossilized Foraminifera.—Evidence of ENSO-induced coastal upwelling may be supported through the $\delta^{18}O$ record of foraminiferal species *Neogloboquadrina dutertrei* and *Globigerina bulloides* pulled up from marine sediments off the coasts of Peru and Southern California (Figs. 4a and 5; Wefer, Dunbar, and Suess, 1983; Dunbar, 1983). These organisms characterize nutrient-dense waters and are therefore good tracers for determining regions where coastal upwelling may have persisted. It has been determined that levels of ^{18}O depletion are directly related to the organism shell size. Large shells – which suggest high rates of fertility and nutrient supply – show a marked depletion in ^{18}O, whereas small shells from the low fertility, low nutrient supply regions express either no change or slight enrichment in ^{18}O values (Wefer, Dunbar, and Suess, 1983). These findings, however, are the opposite, i.e., depletion of ^{18}O in the smaller shells, from the "normal" trend that has been observed in similar specimens from deep-sea sediments. Within a coastal upwelling environment, it is common for the large numbers of juveniles to be produced due to the higher rates of reproduction. Therefore, these isotopic variations within the coastal species are probably a result of climatic analomies (Wefer, Dunbar, and Suess, 1983; Dunbar, 1983). Dunbar (1983) further suggests that the isotopic depletion in surface waters – which caused the depletion of ^{18}O in *G. bulloides* -- coincide with historical proxy of ENSO events in the Southern California region (Fig. 6).

Tropical Ice-cores.—Continuous sequences of oxygen isotope paleodata are also preserved in the snow layers deposited onto tropical glaciers of the Andes. Within the annual variations of ice-cores, $\delta^{18}O$ distribution has been found to provide evidence of atmospheric disruptions that can be correlated with historic proxy of ENSO events. Fluctuations in periods of drought and increased rainfall amounts in the southern highlands of Peru and northern Bolivia are represented by negative and enriched $\delta^{18}O$ values (Thompson, Mosley-Thompson, Thompson, 1992). For example, the Quelccaya ice field in southern Peru (Fig. 7a) experienced a major drought associated with the 1982/83 ENSO. This was apparent by the widespread melting of surface snow during this period. Furthermore, an evaluation of $\delta^{18}O$ values compared with two common ENSO indicators: the SOI and the SST anomalies from Puerto Chicama, Peru (Refer to Fig. 16.6 of Thompson, Mosley-Thompson, Thompson, 1992) clearly shows that much of the historical El Niño phases. Thompson *et. al.* (1992) has found that the reduction in net accumulation during periods of drought is the primary mechanism for the observed $\delta^{18}O$ enrichment. During the wet season – when 80% of the snow supply occurs -- $\delta^{18}O$ values are most negative. Therefore, the physical mechanisms by which ENSO events are recorded in the Quelccaya ice field are very clear.

Tropical Corals.—Coral reefs exist primarily within tropical regions and are widely regarded as the most diverse ecosystem (Kleypas, 1997). Additionally, corals have essentially remained the same throughout the Pleistocene; many contain annual growth bands that record oxygen isotopic variations that can be used to reconstruct histories of SST and upwelling intensities --two common ENSO-related characteristics (Kleypas, 1997; Winter, Goenaga, and Maul, 1991). The timing, location and magnitude of the ocean warming varies from on El Niño to the next, which results in variations chemical and physical oceanic characteristics (NOAA, 1998). Therefore, corals have become a common tool for finding evidence of ENSO conditions from the western Pacific along the equatorial region to the Caribbean. With proper site selection and calibration, corals can provide high quality environmental reconstruction (Dunbar, Braddock, and Wellington, 1996). Both temperature and the $\delta^{18}O$ values of the seawater in which they grow influence coral skeletal $\delta^{18}O$ values. The $\delta^{18}O$ of biogenic calcium carbonate decrease by about 0.22 ‰ for every 1°C rise in seawater temperature (Epstein *et al*, 1953). Most ENSO-related rainfalls are depleted in $\delta^{18}O$ values; therefore, the normal observation is that when salinity of surface waters decreases as a result of intense rainfall, the surrounding seawater and coral $\delta^{18}O$ values also decrease (Dunbar, Braddock, and Wellington, 1996). Recent studies of $\delta^{18}O$ values recorded within coral aragonite of three sites across the pacific basin (Fig. 8) illustrate how closely each of these sites monitor the three important ENSO components: SST, upwelling ,and rainfall intensities (Table 1; Cole, Shen, Fairbanks, and Moore, 1992).

Tarawa Atoll. Evidence of past episodes of isotopically depleted rainfall has been recorded in the corals (Fig. 9) of the Tarawa Atoll (1°N, 173°E), located in the central Pacific. According to the Rayleigh fractionation process (Dansgaard, 1964; Rollison, 1993), $\delta^{18}O$ values of rainwater become depleted during intense periods of convection. As a result, the $\delta^{18}O$ values of the surrounding surface waters become less negative as the mixing of meteoric waters continues (Bird, 1988). These corals lie within the core of the rainfall anomaly generated by the northeastward migration of the Indonesian Low during the warm-phase ENSO conditions. At times, rainfall amounts of >300 mm mo^{-1}, and 500 to 800 mm mo^{-1} may define the precipitation characteristics for this region. These influences have been found to produce significant shifts in the $\delta^{18}O$ values of the corals, which correlate, to historic ENSO events (Cole, Shen, Fairbanks, and Moore, 1992).

Galapagos Islands. Due to there equatorial proximity and location directly east of the Peruvian coast (1°S, 91°W), this island group are particularly sensitive to ENSO-related changes in ocean dynamics; many studies have correlated $\delta^{18}O$ values of Galapagos corals to upwelling-dependant SST's (Druffel 1985; McConnaughey, 1989; Dunbar *et al*, 1991). As in the corals of the Tarawa Atoll, the oxygen isotope records for the Galapagos corals reflect changes in $\delta^{18}O$ values of seawater from intense periods of precipitation during ENSO warm conditions (Cole and Fairbanks, 1990). Likewise, $\delta^{18}O$ histories from Punta Pitt (Isla San Cristobal, Galapagos) coral (at 17-m depth) compared with the SST record from Academy Gay (Isla Santa Cruz, Galapagos; Fig. 10). The significance of these corals are that their geographic proximity within the heart of the region of direct ENSO impacts provides a central site for the east-west Pacific extension of ENSO.

La Parguera. Coral colonies adjacent to a meteorological station of the University of Puerto Rico (Fig. 11) may also be sensitive recorders of chemical and physical characteristics of ENSO events. Scleractinian hermatypic coral *Montastrea annularis* produce clearly discernible high density (HD) and low density (LD) bands of annual growth. Moreover, corals from this region have been observed to live for up to 700 years old (Winter, Goenaga, and Maul, 1991), thus providing an ideal location for studying paleoclimatic conditions. Down-core variations of stable oxygen isotopes have been used successfully to reconstruct accurate histories of temperature and upwelling intensities (Carriquiry *et al*, 1988; Druffel *et al*, 1990; Shen and

Sanfor, 1990). The values of $\delta^{18}O$ were found to vary from –4.96 and –4.08 (Fig. 12). These closely duplicate those of other *M. annularis* coral specimens from Barbados and Jamaica (Winter, Goenaga, and Maul, 1991). A clear connection has been established between the position of the coral isotope sample in relation to the HD (deuterium) band and water temperature. The HD bands are generally depleted in ^{18}O and therefore should most probably have been formed during times of elevated SST's (Winter, Goenaga, and Maul, 1991). Furthermore, these calculated SST's were compared with pelagic SST from the Comprehensive Ocean-Atmosphere Data Set (COADS). The linear correlation coefficient (r) between La Parguera temperatures and COADS pelagic temperatures was r = 0.83. As a result, a wider SST record for ENSO events can be carried eastward to include the Caribbean region for possible sites as paleoclimatic proxy.

CONCLUSION

Originally interpreted as a warning signal from the heavens centuries ago, the Peruvian inhabitants learned quickly that their way of life can and would be occasionally disrupted by the mysterious El Niño. Recently, "El Niño" has become a catch-all term used by the American media to explain the seemingly numerous global climatic disruptions. Needless to say, due to the exorbitant economical and societal impacts that many countries are continually experiencing, the modern world is entrusting the scientific community with finding a solution to El Niño. Experts proved this year that decades of observations, data collection, and computer modeling may have finally provided an accurate means of ENSO prediction. (During the summer of 1997, a decline in trade winds and a rise in SST's observed in the Pacific fit the parameters for an approaching El Niño. Experts soon released a press statement advising the west coasts of North and South America to prepare for strong El Niño-related winter storms to persist through May of 1998.

They were right.). Without a doubt, this incredible outcome would never had become a reality without the vast amount of resources available. Together, $\delta^{18}O$ records within tropical rain waters, ice-cores, foraminifera, and corals has proven to be directly instrumental in the reconstruction of past ENSO conditions. The apparent success of the ENSO prediction has surely secured a future for continued isotopic studies. Moreover, the enlightenment of teleconnections has created the need for more isotopic data covering regions that receive secondary disruptions from an ENSO's initial impact. Despite all of this knowledge of the El Niño/Southern Oscillation Phenomenon that has been achieved, all societies of today – not unlike the Paita sailors of the 17th Century – still do not know where or how El Niño originates. Preferably, neither the general public, nor our political leaders will become complacent with the success of the 1997-98 prediction. Rather, continued support is needed for those dedicated individuals attempting to piece together the fragmented world of ENSO.

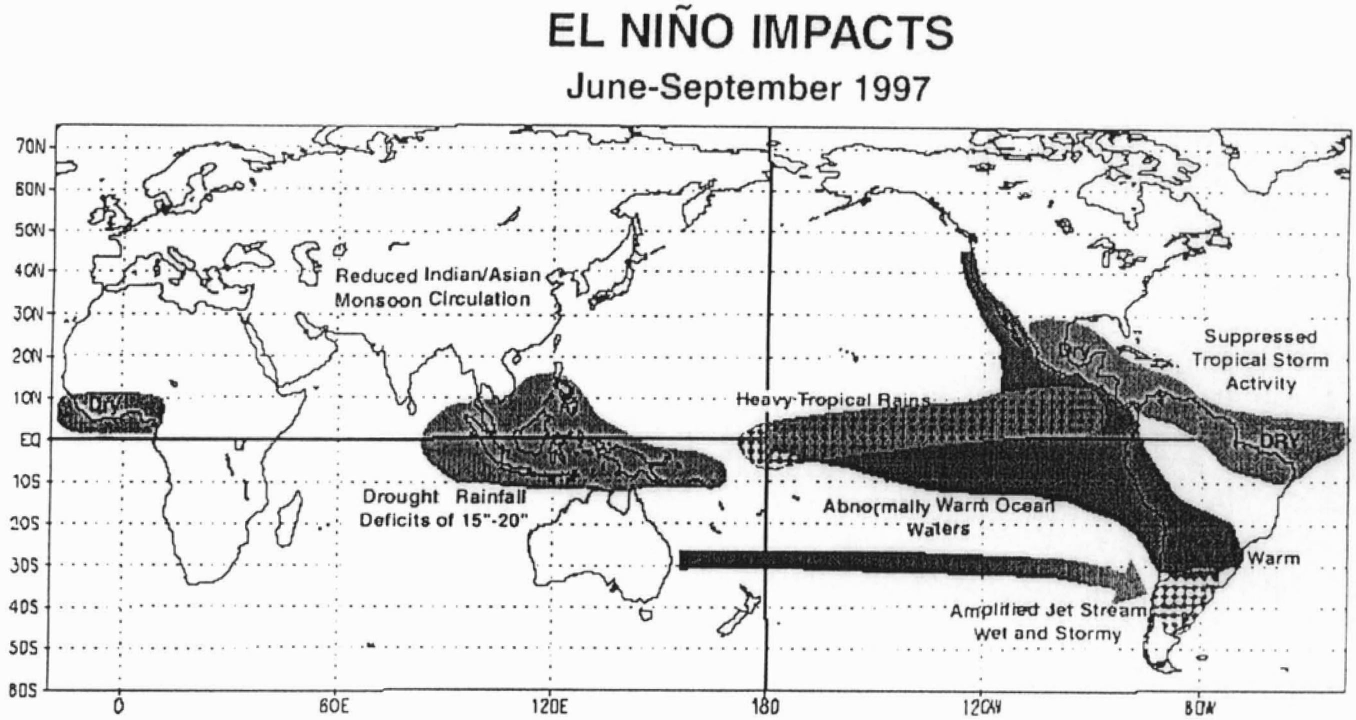

Figure 1: Global view of known ENSO teleconnections recorded during 1997-98 ENSO conditions. (From NOAA, 1997)

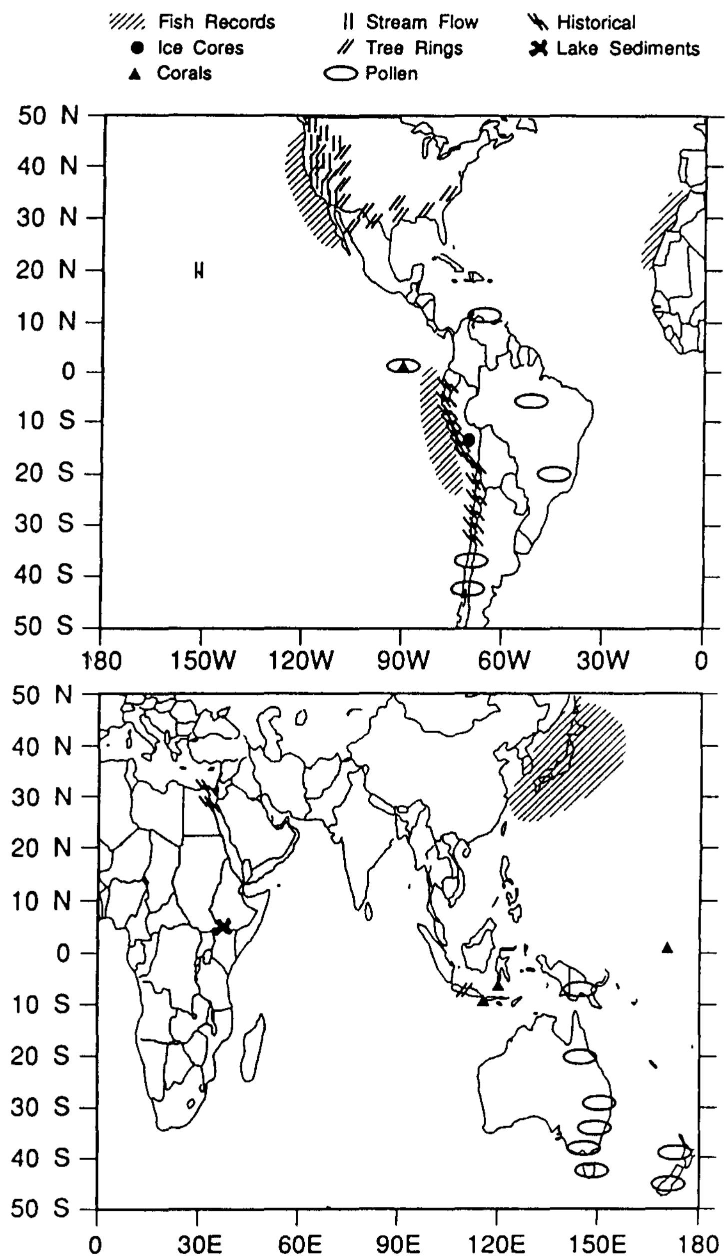

Figure 2: Various localities of paleoclimatic proxies currently used for monitoring ENSO-related conditions. (From NOAA, 1997)

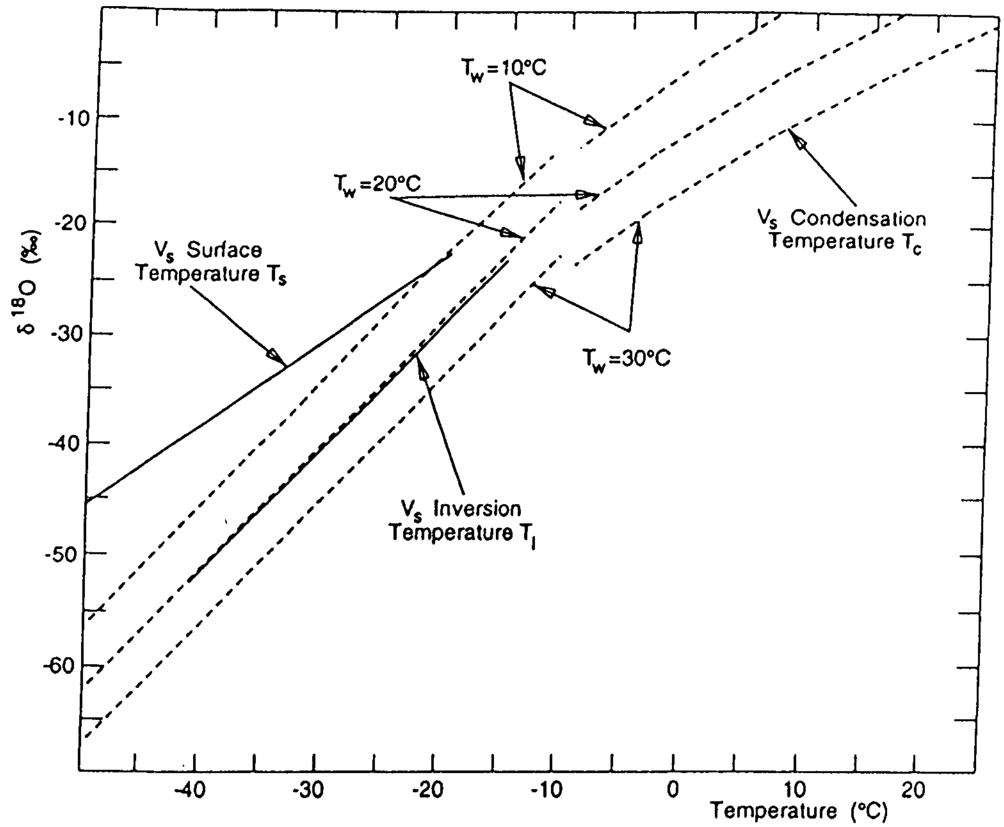

Figure 3: Fractionation affect of temperature to oxygen isotopes.
(From Rollison, 1993)

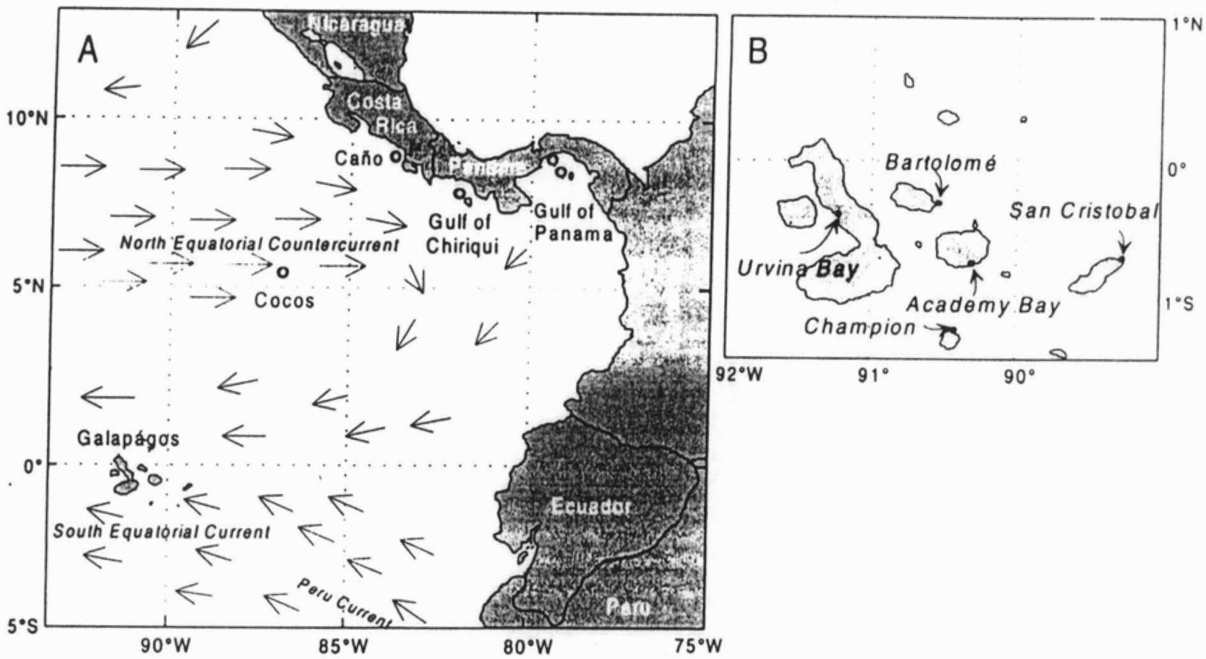

Figure 4: (A) Approximate region off Peruvian coastline where species of *N. dutertrei* used by Wefer *et. al.*, 1983. (B) Group of islands that make up the Galapagos Islands, eastern Pacific. (From Dunbar, 1983)

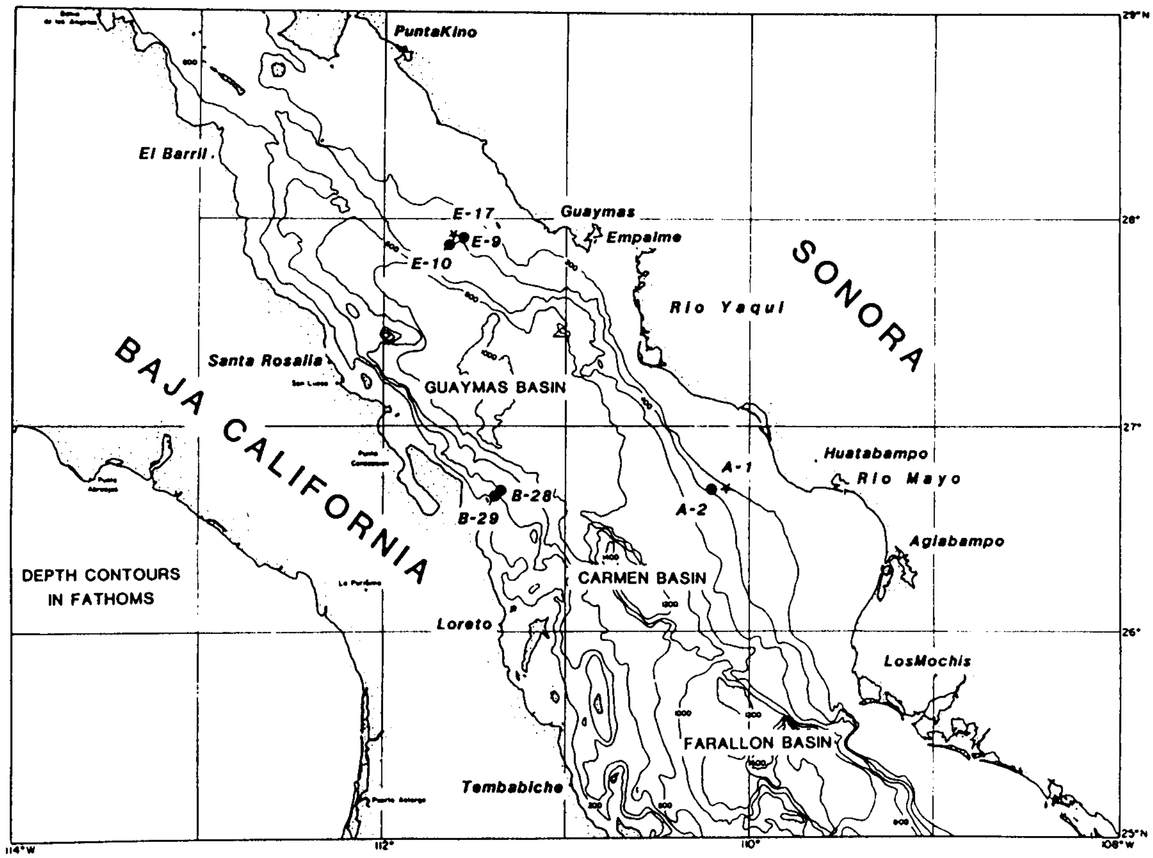

Figure 5: Sediment core sites used by Dunbar (1983) for correlating $\delta^{18}O$ values of *G. bulloides* with historic coastal upwelling, Gulf of California. (From Dunbar, 1983)

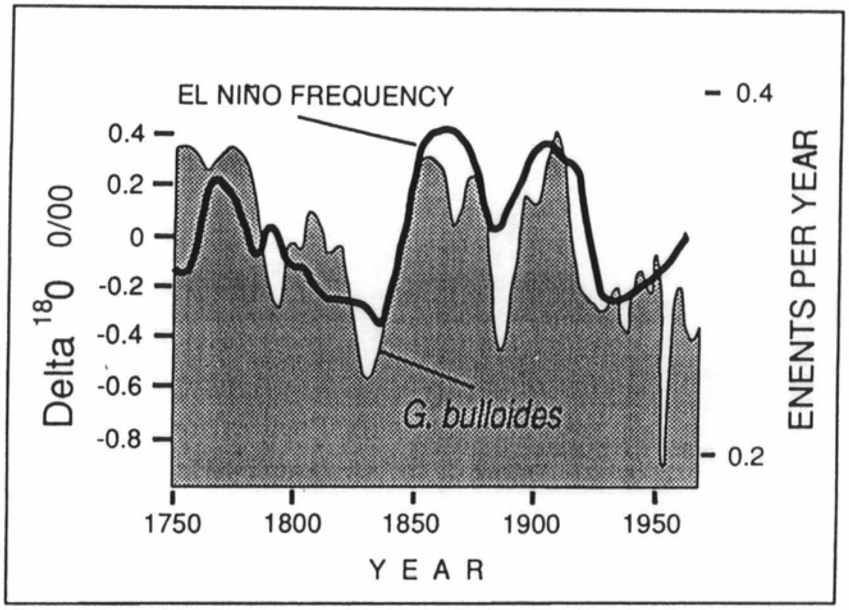

Figure 6: Relationship of $\delta^{18}O$ values of *G. bulloides* to El Niño recorded frequency. (From Dunbar, 1983)

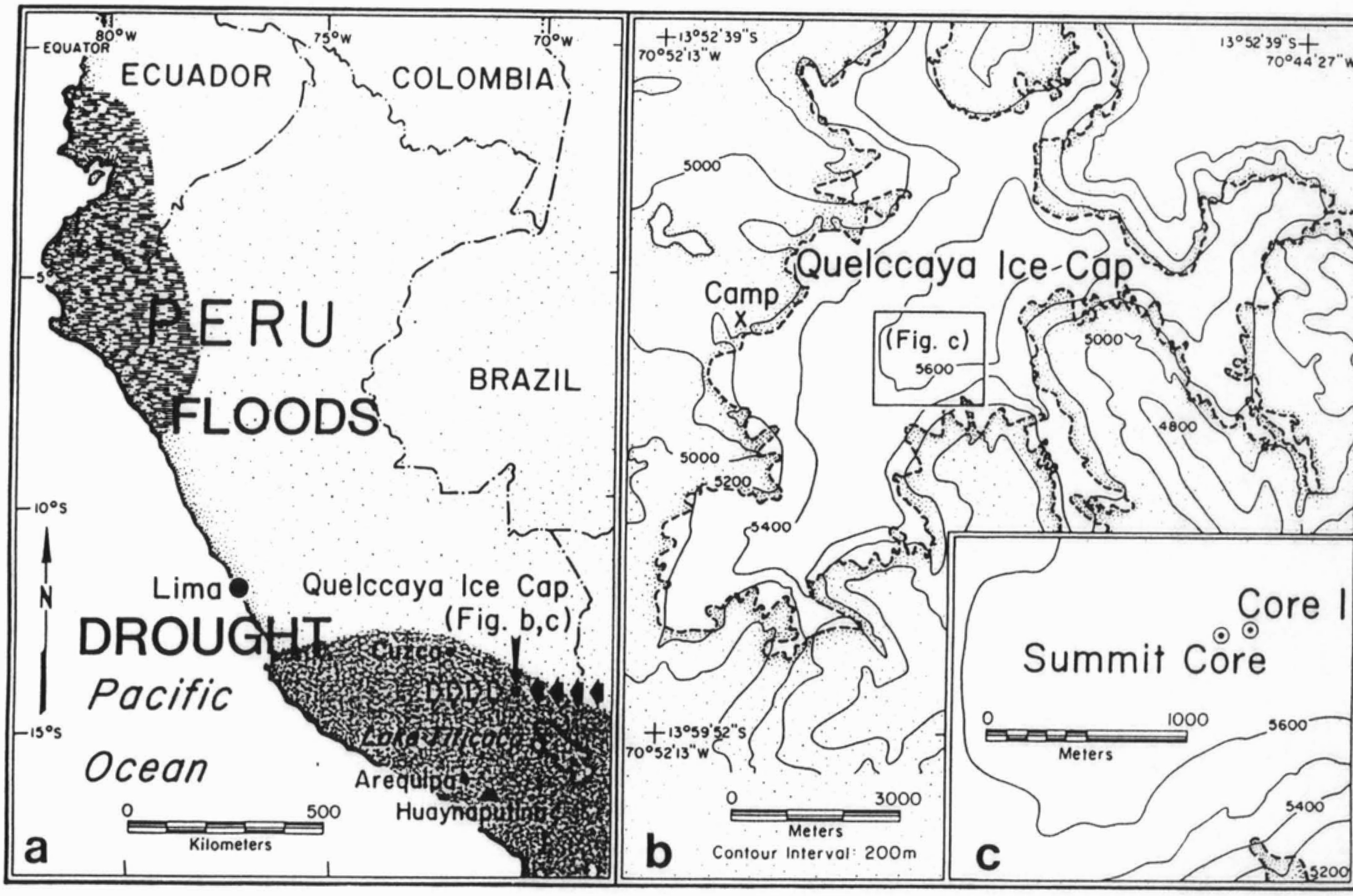

Figure 7: (A) Proximity of the Quelccaya ice cap to the region affected by ENSO-caused drought. (From Thompson *et. al.*, 1992)

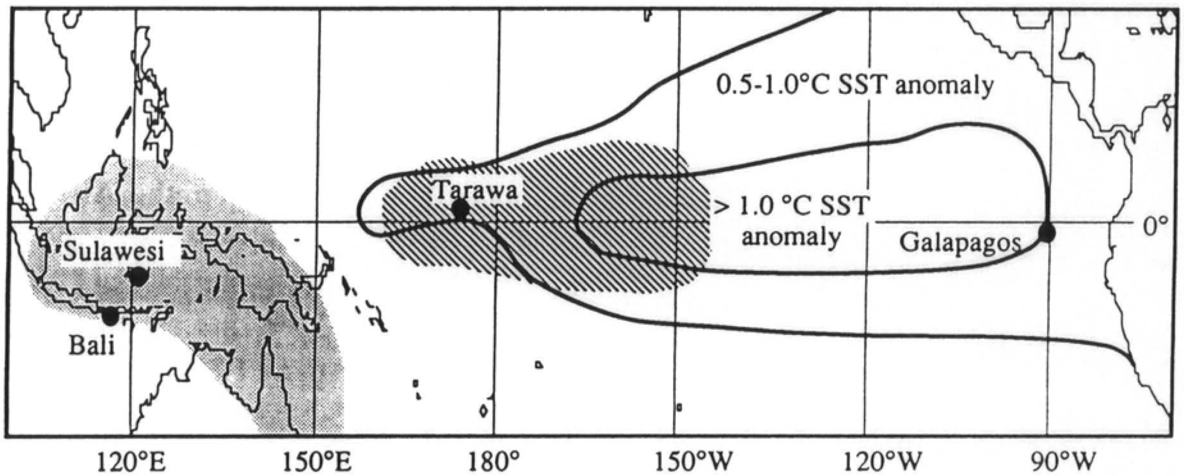

Figure 8: Location of the Tarawa and Galapagos corals; La Paraguera is located directly east of the Gulf of Mexico. (From Cole, Shen, Fairbanks, and Moore, 1992)

Coral sites and available records

Site	Location	Major ENSO impacts	Coral records	Reference[a]
Galapagos	1°S, 90°W	Upwelling suppressed		
		Warm SST	$\delta^{18}O$	1,2
		Low nutrients	Cd, Ba	3,4
		Increased rainfall	$\delta^{13}C$(?)	2
Tarawa Atoll	1°N, 172°E	Intense rain	$\delta^{18}O$	5
		Trade winds weaken/reverse	Mn	6
Bali	8°S, 115°E	Weakened monsoon, longer dry season	$\delta^{18}O$	This chapter

[a]References: 1, Druffel (1985); 2, McConnaughey (1989); 3, Shen et al. (1987); 4, Lea et al. (1989); 5, Cole and Fairbanks (1990); 6, Shen et al. (1992a).

Table 1: Correlation of coral $\delta^{18}O$ values to the major components of ENSO events. (From Cole, Shen, Fairbanks, and Moore, 1992)

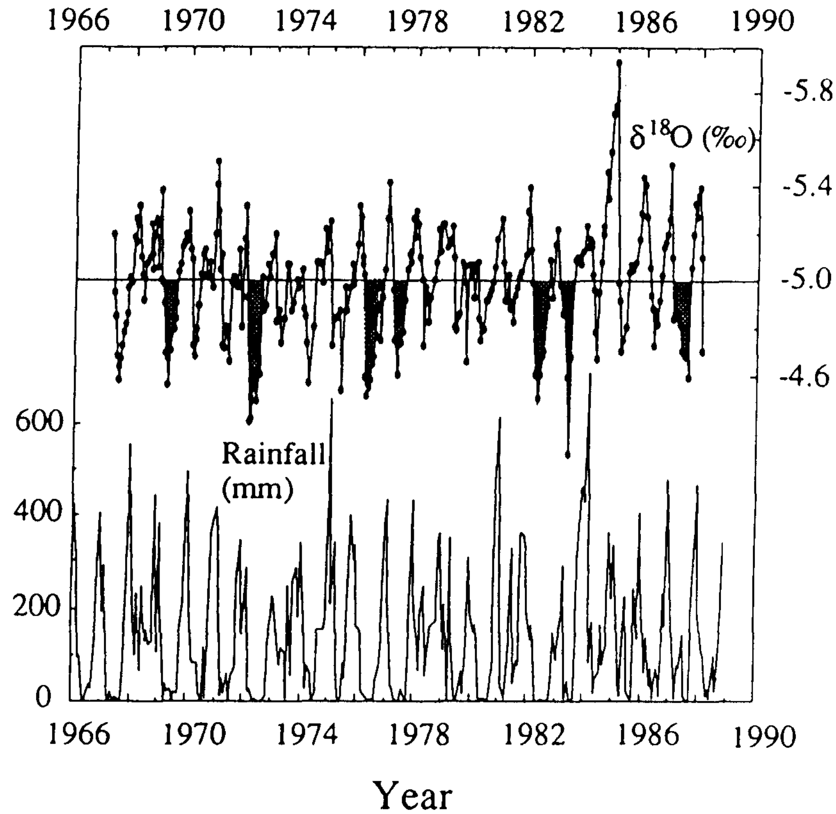

Figure 9: A 24-year isotopic record of Tarawa corals and the correlation with recorded rainfall amounts. (From Cole, Shen, Fairbanks, and Moore, 1992)

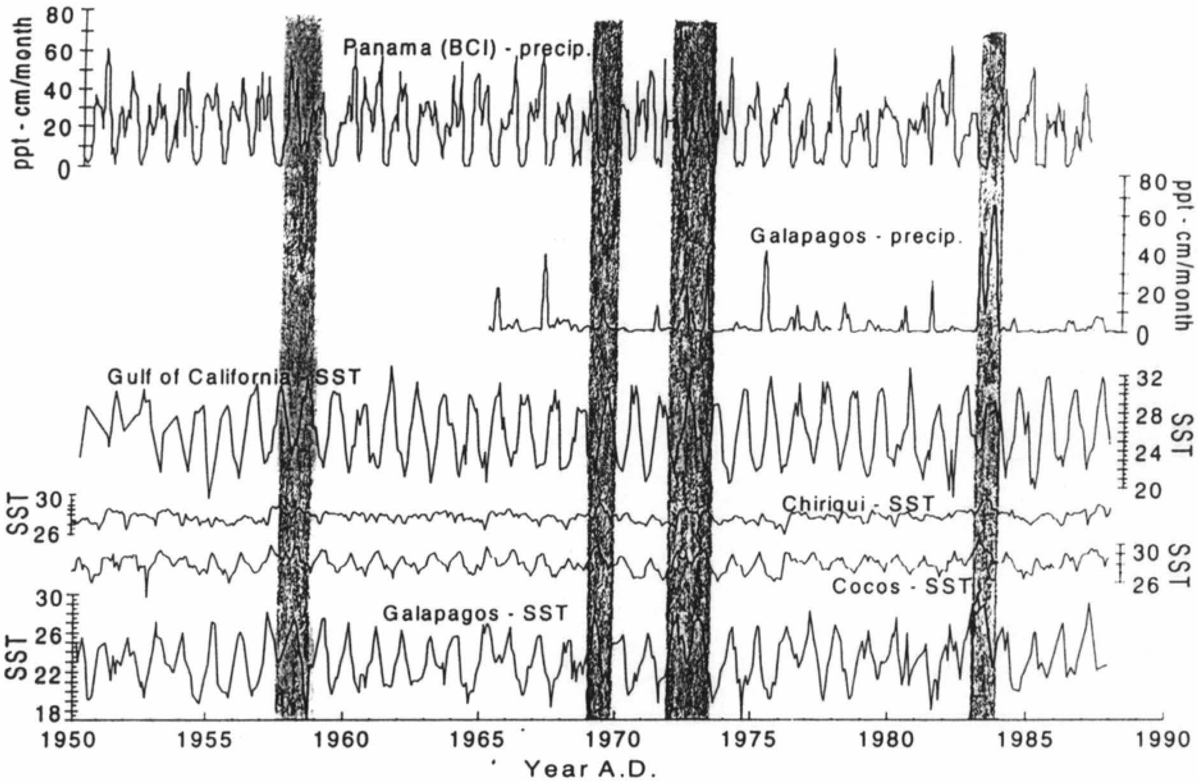

Figure 10: A 30-year record correlating precipitation intensities (cm mo^{-1}) with SST's of various tropical regions of the eastern Pacific. Shaded bars represent ENSO events. (From Cole, Fairbanks, and Shen, 1993)

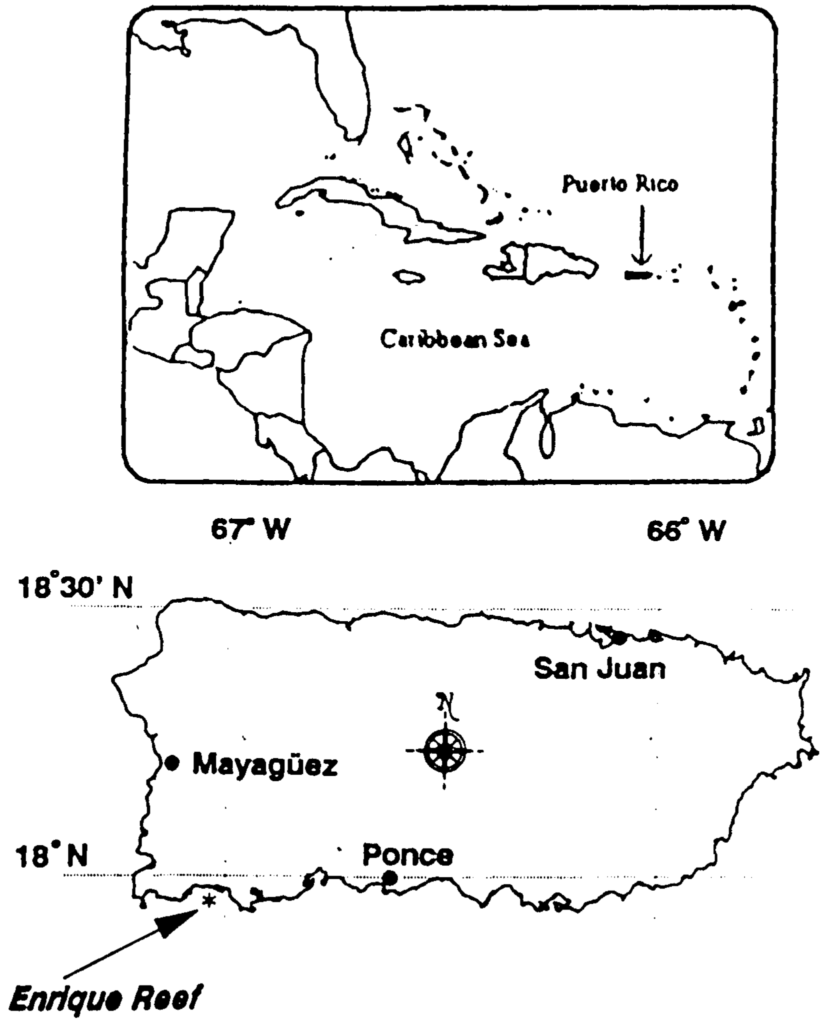

Figure 11: Location of the La Parguera coral study site. (From Winter, Goenaga, and Maul, 1991)

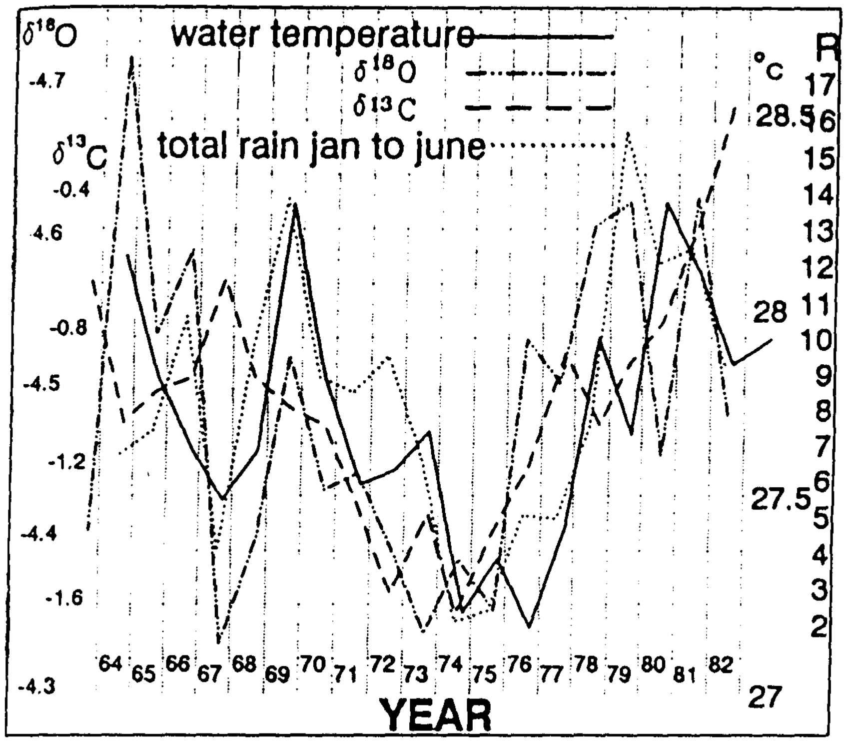

Figure 12: The direct relationship of $\delta^{18}O$ values of the La Paraguera corals with water temperature and rainfall fluctuations. (From Winter, Goenaga, and Maul, 1991)

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