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A coral-based reconstruction of Intertropical Convergence Zone variability over Central America since 1707

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Abstract. Seasonal movements of the Intertropical Convergence Zone (ITCZ) control precipitation patterns and cloud cover throughout the tropics. In this study we have reconstructed seasonal and interannual variability of the eastern Pacific ITCZ from 1984 to 1707 using subseasonal $\delta^{18}O$ analyses on a massive coral from Secas Island (7°59'N, 82°3'W) in the Gulf of Chiriquí, Panamá. The land area that drains into the Gulf of Chiriquí has served to amplify the rainfall effect on nearshore surface waters and coral $\delta^{18}O$ composition. During the protracted wet season in Panamá, the $\delta^{18}O$ of precipitation ($\delta^{18}O_{ppt}$) is reduced on average by 10‰ and sea surface salinity (SSS) along the western coast is reduced up to 11‰. Calibration of the coral $\delta^{18}O$ from Secas Island against instrumental sea surface temperature (SST), SSS, precipitation and $\delta^{18}O_{ppt}$ data indicate that seasonal rainfall induced variations in seawater $\delta^{18}O$ are responsible for ~80% of the annual $\delta^{18}O$ variance. Past El Niño-Southern Oscillation (ENSO) events are recorded as minor 0.2 to 0.4‰ $\delta^{18}O$ changes superimposed on the dominant annual $\delta^{18}O_{seawater}$ and salinity variations. The annual cycle in coral $\delta^{18}O$ (average 0.9‰) accounts for the largest component of variance at 51% and is the direct result of the annual northward expansion of the eastern Pacific ITCZ. The regularity of the reconstructed seasonal ITCZ cycle indicates that over the length of the record the zone of maximum rainfall in the eastern Pacific has always expanded north to at least Panamá in every northern hemisphere summer. Significant interannual and interdecadal $\delta^{18}O$ oscillations occur at average periods near 9, 3-7 (ENSO band), 17 and 33 years (listed in order of decreasing variance). Over the past 20 years similar decadal shifts are apparent in coral $\delta^{18}O$ from nearshore in the Gulf of Panamá. SST data spanning the last 40 years show no decadal changes. This indicates that decadal oscillations in the Gulf of Chiriquí $\delta^{18}O$ record are regional features not related to SST changes, but are caused by ITCZ precipitation effects on the $\delta^{18}O$ of seawater. A 9-year period in Panamá precipitation supports this conclusion and provides a potential link between interannual coral $\delta^{18}O$ variations and ITCZ precipitation. It is also shown that the period of the average 9-year interannual period in coral $\delta^{18}O$ varies from ~7.5 years to ~11.8 years. Variance near 11 years is strongest throughout the 1800s, however, a poor direct correlation with sunspot number and solar irradiance leaves the origin of this interannual oscillation in question. The $\delta^{18}O$ time series also contains a long-term trend of -0.40‰ suggesting an increase in precipitation and/or SST since the early 1800s. As the Gulf of Chiriquí coral $\delta^{18}O$ time series is the first paleoclimatic record of past variations in the ITCZ, other seasonal-resolution reconstructions of the past behavior of the ITCZ are required to test whether the interannual and long-term variability observed in the eastern Pacific ITCZ is more than regional in scale.

Introduction

The onset of summer monsoon rains in Central America, North Africa, India and Southeast Asia is triggered by the annual northward expansion of the Intertropical Convergence Zone (ITCZ). The ITCZ is a narrow latitudinal zone of atmospheric convection and clouds in the equatorial low-pressure trough where moisture-laden trade winds converge on the warmest regions of the ocean (Figure 1). The ITCZ is a primary feature of the atmospheric hydrologic cycle and marks the boundary between northern and southern hemisphere Hadley circulation (see *Rasmusson and Arkin* [1993], *Waliser and Gautier* [1993], *Chahine* [1992], and *Philander* [1990] for review). Over 40% of global precipitation falls within 15° of the equator, primarily in the towering convective systems of the equatorial trough region. The ITCZ is generally, but not

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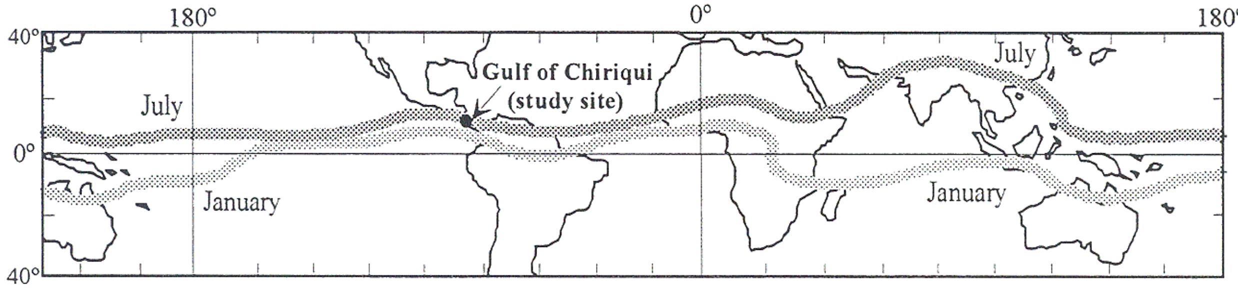

Figure 1. Schematic representation of the average position of the Intertropical Convergence Zone (ITCZ) in July and January. The ITCZ occupies its most northerly position during the northern Hemisphere summer. Arrow marks the position of the study site at Secas Island in the Gulf of Chiriquí, Panamá.

necessarily, found over that portion of the ocean with sea surface temperatures (SST) greater than 27.5°C. Studies have shown that although high SSTs are a necessary condition for convection, they are not a sufficient condition, and convection is absent in many areas where SSTs > 27.5°C are found [*Gadgil et al.,* 1984; *Graham and Barnett,* 1987]. The annual north-south movements of the ITCZ regulate seasonal variability in the tropics. The ITCZ reaches its most northerly position in July and its most southerly position in January. The narrow latitudinal extent of the ITCZ produces sharp north-south rainfall gradients. Because of these gradients, *Philander* [1990] suggests that even small variations in the past position of the ITCZ could dramatically affect rainfall distribution in the tropics and sub-tropics.

In the Pacific there is also a pronounced east-west component of tropical convection that operates at periods ranging from 2 to 10 years. A large region of ascending air over the western Pacific is linked by high-altitude winds to a descending limb in the eastern Pacific outside of the ITCZ. This east-west zonal cell that oscillates between two extreme phases (El Niño and anti-El Niño) was termed Walker Circulation by *Bjerknes* [1966] and is the basis for the Southern Oscillation (SO), one of the most extensively studied circulation systems. The SO system of zonal convection and pressure gradients in the tropical Pacific has been related to interannual variability throughout the tropics through study of meteorological and paleoclimatic data [*Cane,* 1986; *Enfield,* 1989; *Philander,* 1990; *Cole and Fairbanks,* 1990; *Cole et al.,* 1993; *Dunbar et al.*, 1994]. The phase of the SO is also closely tied to that of the seasonal cycle and the ITCZ in the western and central Pacific. However, outside this region the linkage becomes less clear.

Although the ITCZ is the dominant mode of seasonal variability in the tropics, and is an integral part of tropical climatology, there has never been a seasonal-scale reconstruction of ITCZ rainfall over the past several centuries. Documenting past changes in the ITCZ is important for several reasons. As catastrophic flooding periodically accompanies variability in the ITCZ, it is important to develop a better understanding of this fundamental component of the tropical climatic system. Additionally, the effect of cloud cover is one of the greatest uncertainties in the study of climatic change [*Senior and Mitchell,* 1993]. Clouds account for ~2/3 of the planetary albedo, increasing the reflectance of incoming solar radiation and potentially cooling climate. However clouds also trap outgoing long wave radiation, and may contribute to climatic warming. Satellite monitoring shows that the convective clouds in the ITCZ strongly correlate with the distribution of atmospheric water vapor and precipitation [*Chahine,* 1992; *Spencer,* 1993]. Furthermore, by correlating satellite estimates of precipitation with rain gauge measurements, *Spencer* [1993] has demonstrated that the eastern Pacific ITCZ is associated with up to 5 m of annual rainfall. Long-term changes in ITCZ precipitation and cloud cover over the last several centuries may provide clues about the anthropogenic influence on climate. Information about the intensity and seasonal migration of the ITCZ during the end of the Little Ice Age (LIA) would also increase our understanding of how seasonal variability in the tropics responded to this "base state" change in climate. The LIA, which ended in the late 1800s, is the last of several geographically widespread "neoglacial" events that occurred in the Holocene [*Denton and Karlen,* 1973; *Porter,* 1981; *Grove*, 1988; *Overpeck,* 1989]. Information concerning past changes in the ITCZ would also aid climate modelers who are developing models of the SO and the coupled ocean-atmosphere system. Current models successfully reproduce the east-west movements of the convergence zone in the central and western Pacific; however, they are poor at simulating seasonal and interannual ITCZ shifts, which are important features of the SO [*Philander,* 1990; *Senior and Mitchell,* 1993].

As a first step in examining past variability of the ITCZ, we present a 277-year coral $\delta^{18}O$ record from Panamá that has preserved seasonal, annual, and decadal variations in eastern Pacific ITCZ-related precipitation from 1984 to 1707. The signal carrier is a large specimen of the massive coral *Porites lobata* collected at Secas Island (designated S1) in the Gulf of Chiriquí, Panamá (Figures 1 and 2). The Gulf of Chiriquí is characterized by a small (1-2°C) and irregular annual temperature range; however, annual variations of coastal Panamá sea surface salinity (SSS) and precipitation $\delta^{18}O$ ($\delta^{18}O_{ppt}$) vary as much as 11 and 12‰, respectively, as a result of the pronounced wet season. This strong annual signature has been preserved in the $\delta^{18}O$ composition of the S1 coral. The relative thermal stability of the Gulf of Chiriquí (range 27-29°C) and large ITCZ-driven seasonal SSS and $\delta^{18}O_{ppt}$ range provide a unique opportunity to use coral skeletal $\delta^{18}O$ to examine past changes in ITCZ precipitation. To our knowledge this is the first multicentury coral record of seasonal and interannual variations in the ITCZ.

The rationale for using massive hermatypic corals to reconstruct past variability of the ITCZ is based on previous studies that have utilized long coral records to resolve interannual and decadal-scale changes in surface ocean conditions over the past several centuries [e.g. *Druffel,* 1982; *Isdale,* 1984; *Dunbar et al.,* 1991, 1994; *Shen et al.,* 1991; *Cole et al.,* 1993]. Massive reef corals can live for centuries

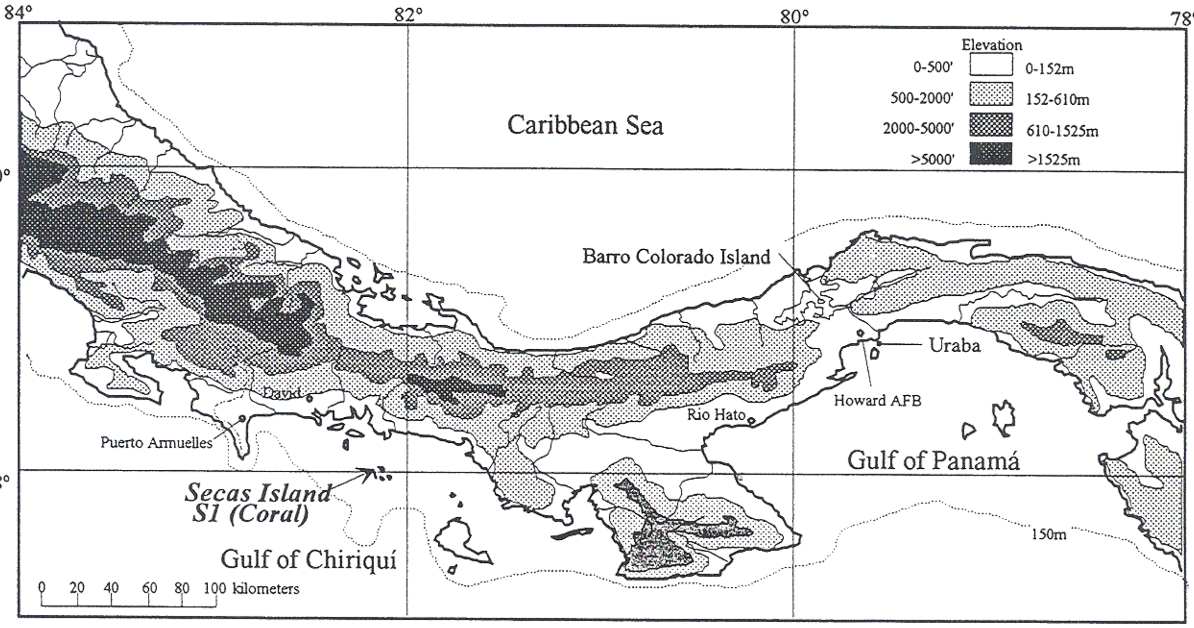

Figure 2. Detailed map of the study area showing the location of Secas Island and the S1 coral in the Gulf of Chiriquí. Other locations discussed in the text are also indicated. The Panamánian Highlands are contoured with shading. The Highlands block the trade winds from influencing the Gulf of Chiriquí during the dry season which maintains the relative thermal stability near Secas Island.

and grow continuously at rates of several millimeters to a couple of centimeters per year with most species producing annual growth bands. Growth bands are expressed as couplets of low- and high-density portions of the coral skeleton that serve as time markers for the development of long chronologies. Previous studies have shown that the $\delta^{18}O$ composition of accreting skeletal aragonite can accurately record seasonal and interannual changes in SST, SSS, and $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$) [*Dunbar and Wellington,* 1981; *Weil et al.,* 1981; *Swart,* 1983; *McConnaughey,* 1989; *Cole and Fairbanks,* 1990; *Shen et al.,* 1992; *Cole et al.,* 1993; *Dunbar et al.,* 1994].

Central American Climate, Hydrography, and the ITCZ

The zone of maximum annual mean rainfall in the eastern Pacific and Central America coincides with the ITCZ [*Horel,* 1982; *Spencer,* 1993] that seasonally migrates between the equator in March and April to ~10°N in August and September [*Horel,* 1982] (see Figure 1). Along the equator and adjacent coastal locations in the central and eastern Pacific a single pronounced rainfall maximum occurs in March and April. Between 8°N and 12°N across Panamá and Costa Rica, the wet season occurs from May through November when the ITCZ occupies its most northerly position (Figure 3). *Mitchell and Wallace* [1992] have shown that in the eastern Pacific, seasonal movements of the ITCZ are directly tied to surface winds and the equatorial oceanographic cold tongue. They also argue that positive feedbacks involving both zonal and meridonal wind components contribute to the robustness of the ITCZ-cold tongue complex in the eastern Pacific.

Rainfall anomalies that develop in the central Pacific during El Niño do not reach Central America, Panamá, the Caribbean, or northeastern South America and thus these regions tend to remain relatively dry [*Ropelewski and Halpert,* 1987; *Kiladis and Diaz,* 1989]. During an El Niño warm event in the eastern Pacific, the ITCZ expands and intensifies equatorward, tracking the warm water pool and bringing intense rainfall to areas as far as 8°S [*Philander,* 1990; *Deser and Wallace,* 1990]. During the high index phase of the SO (anti-El Niño, cool

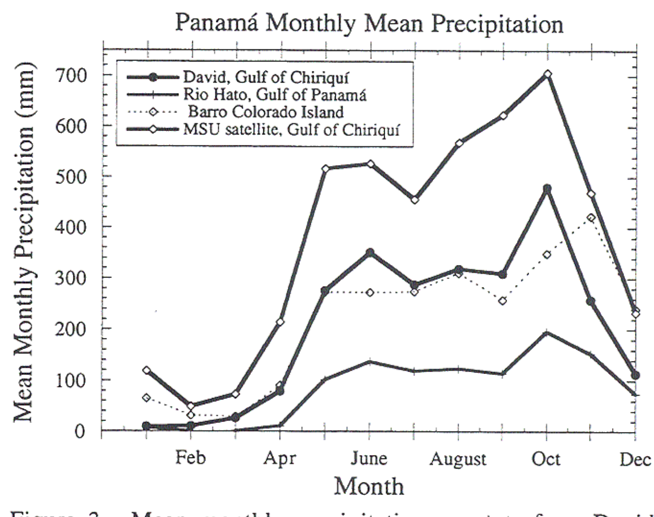

Figure 3. Mean monthly precipitation amounts from David (Gulf of Chiriquí), Barro Colorado Island (Gulf of Panamá), Rio Hato (Gulf of Panamá). Also shown is Microwave Sounding Unit (MSU) satellite estimated. precipitation for the 2.5°x2.5° grid block offshore from the Gulf of Chiriquí (from R. Spencer, NASA; see *Spencer,* 1993). The dry season lasts from January through April, when the ITCZ has moved to a southerly position near the equator and trade winds induce upwelling in the Gulf of Panamá. The timing of the pronounced wet season is coherent throughout Panamá, with more precipitation falling over the ocean.

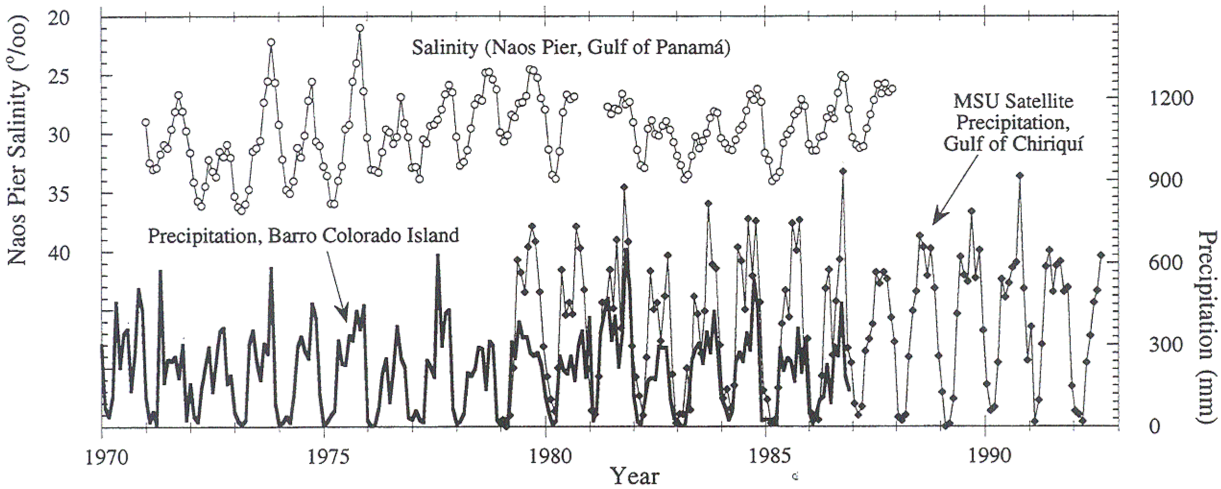

Figure 4. Monthly precipitation from Barro Colorado Island and MSU (see Figure 3), and monthly sea surface salinity (SSS) at Naos Pier of the Panamá Canal in the Gulf of Panamá. During the wet season, SSS is reduced by 5 to 12°/oo.

phase) there is no discernible effect on rainfall in Panamá [*Ropelewski and Halpert,* 1989]. Rainfall throughout Central America also tends to be greater than normal the summer before an El Niño and lower than normal the fall/winter following an El Niño [*Kiladis and Diaz,* 1989].

Surface waters along the Pacific coast of Panamá have some of the lowest salinities in the tropics as a result of freshwater influx during the wet season. Numerous small rivers in Panamá influence salinity in the coastal zone [*Forsbergh,* 1969; *Bennett,* 1966]. *Forsbergh* [1969] calculates that the combined runoff into the Panamá Bight alone is 64% of that of the Mississippi River. SSS data at the Pacific portal of the Panamá Canal (Naos Pier, Smithsonian Tropical Research Institute) from 1971 to 1987 show an annual range of salinity from 5 to > 11°/oo (Figure 4). Comparison of monthly average salinity in the Gulf of Panamá to monthly precipitation from Barro Colorado Island (Figures 2 and 4) shows that the annual salinity minimum occurs in September and November at the height of the wet season. *Bennett* [1966] compiled SSS data in the eastern Pacific into monthly charts of average SSS. In the Gulf of Chiriquí, SSS varies from a high of 33.5°/oo during the dry season to a low of 24°/oo in November (Figures 5a and 5b). During November the area affected by this low-salinity water extends from the Gulf of Panamá to the Gulf of Chiriquí and as far as 200 to 300 km offshore (Figure 5a). Conductivity-temperature-depth (CTD) salinity profiles collected over the last seven decades for a 2x2° area offshore from the Gulf of Chiriquí also show a salinity reduction during the wet season [*National Oceanographic Data Center (NODC),* 1991]. The profiles document a salinity reduction of up to 4°/oo during the wet season; however, it is important to note that none of the profiles were collected directly in the Gulf of Chiriquí near Secas Island. Surface salinity within the Gulf of Chiriquí would have experienced larger annual variations as evidenced by nearshore SSS data compiled by *Bennett* [1966] (Figure 5).

From January to April when the ITCZ has moved to a position south of Panamá, the NE trade winds that feed the convection in the ITCZ blow unimpeded across central Panamá through a gap in the Panamanian central mountain range (Figure 2). The Gulf of Panamá is subject to strong upwelling during these months and a resultant drop in SSTs [*Forsbergh,*

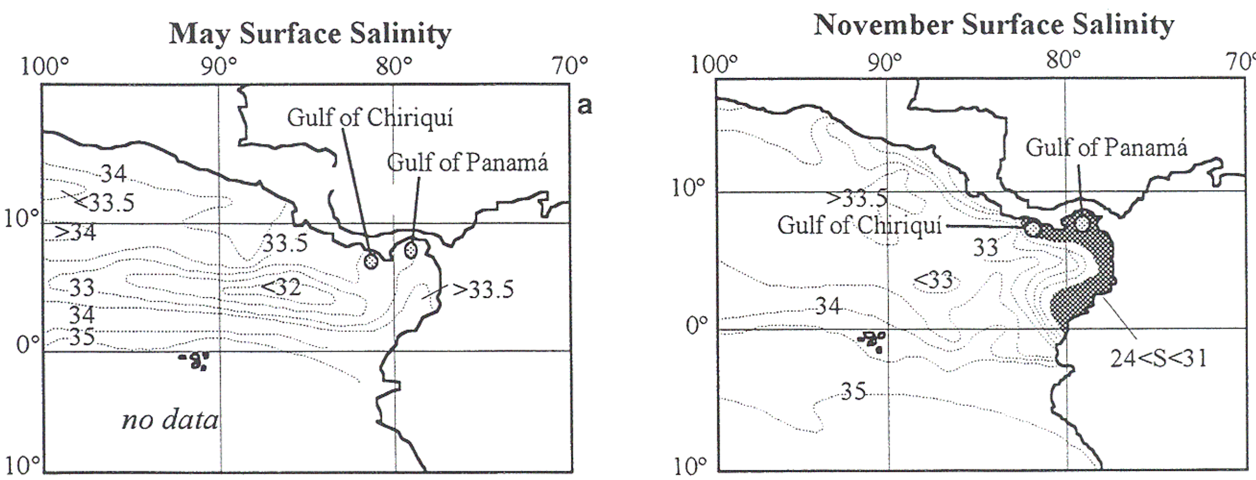

Figure 5. (a) May surface salinity in the Panamá Bight (contour interval 0.5°/oo) [from *Bennett,* 1966]. (b) Same as in Figure 5a except for November. During the height of the wet season the region of low salinity extends from Colombia to the Gulf of Chiriquí.

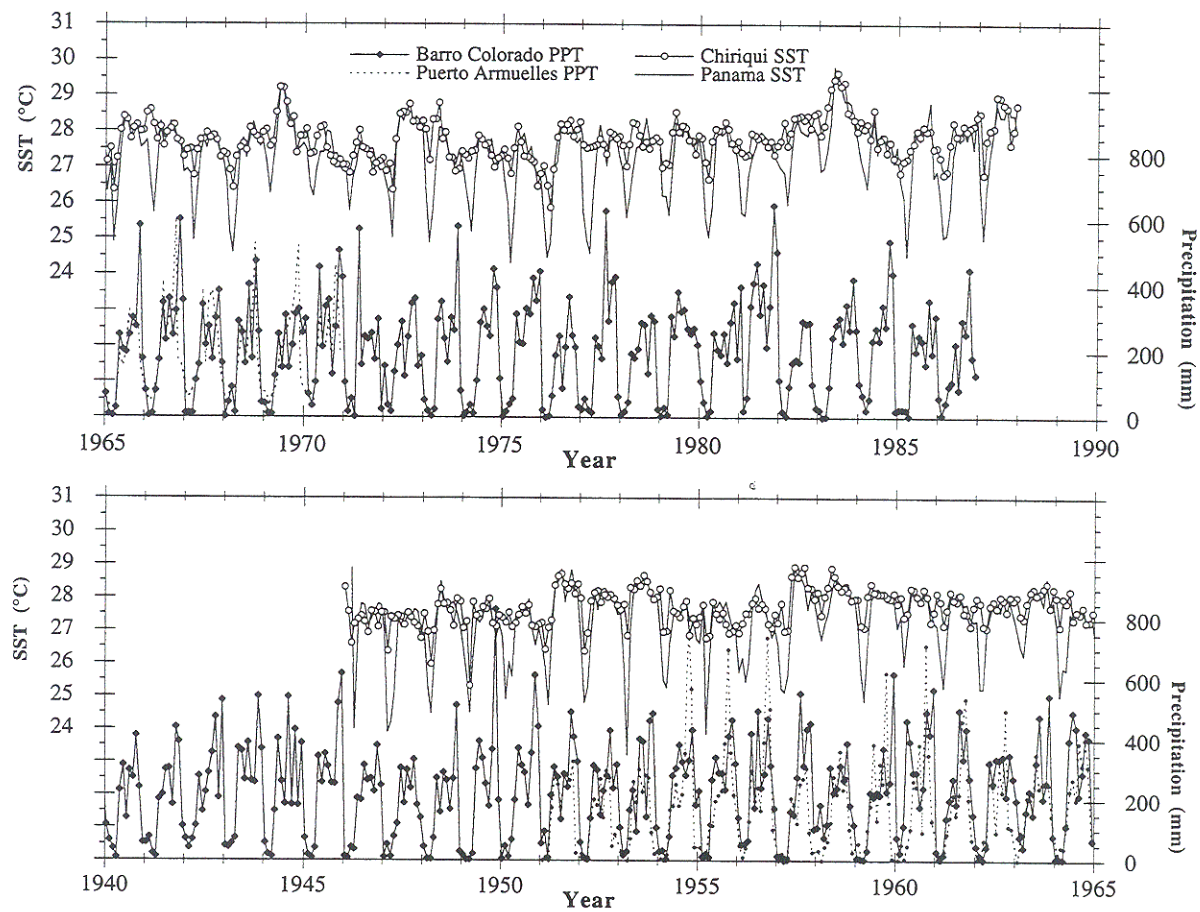

Figure 6. COADS SST data from the gulfs of Chiriquí (2°x2° grid centered at 7°N, 82°W) and Panamá (centered at 7°N, 80°W) for 1946 to 1987, and monthly precipitation data from Barro Colorado Island (Gulf of Panamá, 1940-1987) and Puerto Armuelles (Gulf of Chiriquí, 1951-1971).

1969; *Glynn,* 1977] (Figure 6). The southward migration of the ITCZ also brings the annual dry season to Panamá. During some extended periods of the dry season, no precipitation will fall over large regions of Panamá. The regularity of the alternation of wet and dry seasons in Panamá is also apparent in the precipitation record shown in Figure 6. *Windsor* [1990] compiled monthly rainfall totals at Barro Colorado Island (Figure 2) that span the interval from 1925 to 1987. Other shorter rainfall records from Central America [*World WeatherDisk*^{TM}, 1990], and microwave sounding unit (MSU) satellite-estimated precipitation from 1979 to 1992 for the 2.5x2.5° latitude-longitude block offshore from the Gulf of Chiriquí (data from R. Spencer, NASA) demonstrate that the onset and termination of the summer rainy season is synchronous throughout the Gulf of Chiriquí region. Comprehensive Ocean Atmosphere Data Set (COADS) SST data from 2x2° latitude-longitude blocks that include the Gulfs of Chiriquí and Panamá show that SST in the Gulf of Panamá drops 6° to 8°C during upwelling season and only 1° to 2°C in the Gulf of Chiriquí. In the Gulf of Chiriquí, the annual SST variations are minimal due to partial NE trade blocking by the Panamanian central mountain range and the absence of upwelling [*Glynn,* 1977] (Figure 2). Even during extreme El Niño events, SST increases a maximum of 1.5° to 2°C in the Gulf of Chiriquí. This situation results in the absence of a pronounced and regular seasonal SST signal in the Gulf of Chiriquí (Figure 6).

Two main oceanic current systems influence the open-ocean area off the Gulf of Chiriquí and Costa Rica [*Wyrtki,* 1974; *Hall et al.,* 1992]. From May to January the prevailing currents are related to the eastward flowing Equatorial Counter Current (ECC). During February to April the ECC withdraws to the west and surface waters circulate in a cyclonic eddy which feeds into the North Equatorial Current [*Hall et al.,* 1992].

Corals Along Panamá's Pacific Coast

The coral communities and coral reefs in Panamá are relatively small and contain few coral species [*Glynn et al.,* 1972; *Dana,* 1975; *Glynn and Macintyre,* 1977]. The principal reef building corals are *Pocillopora damicornis, Pocillopora elegans* (both branching species), and *Porites lobata.* Other hermatypic corals of minor importance are *Pavona clavus, Pavona gigantea, Pavona varians,* and several other *Pocillopora spp.* Primary structural development is confined to sites protected from direct wave assault.

Catastrophic El Niño events can have a profound effect on reef corals in Panamá as evidenced by the impact of the 1982-1983 El Niño. The COADS SST data (Figure 6) indicate that the 1982-1983 El Niño resulted in the greatest SST anomaly in the last 40 years. Widespread coral bleaching and mortality occurred throughout the gulfs of Panamá and Chiriquí [*Glynn,* 1983, 1990] Bleaching in corals can result in the cessation of growth for several months and/or partial or total mortality of a

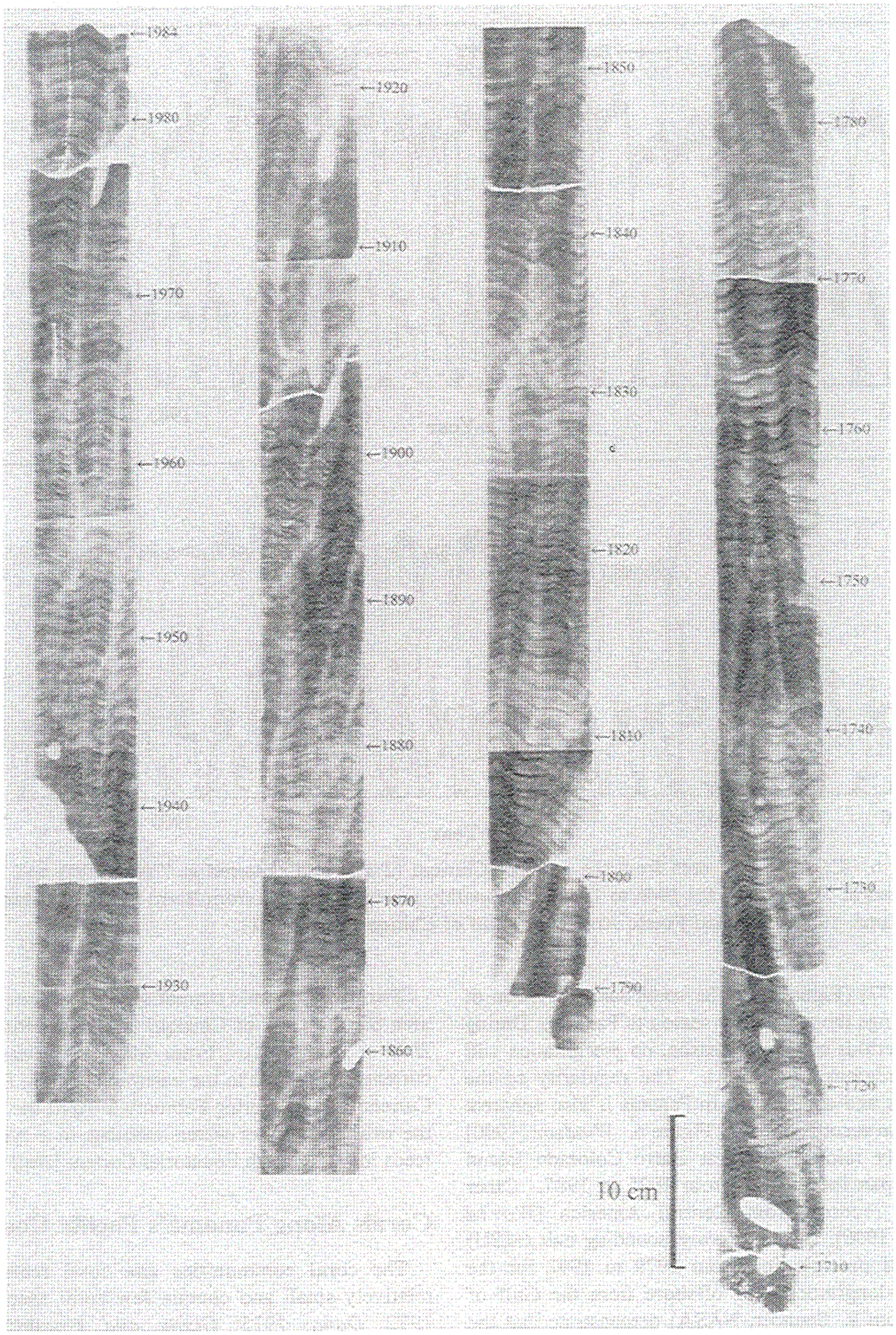

Figure 7. X ray positive collage of specimen of *Porites lobata* from Secas Island (S1) in the Gulf of Chiriquí. Core was collected from 3 m water depth in June 1984 and extends to 1707 based on band counting and annual $\delta^{18}O$ cycles.

colony. Based on a coral census study taken during and after the 1982-1983 El Niño, *Glynn* [1983] estimated that as many as 75% of corals were killed in the Gulf of Chiriquí as a result of elevated SST.

Analytical Methods

During June 1984 a 2.8-m core was collected from a living colony of *Porites lobata* from 3-m water depth at Secas Island (7°59' N, 82°3' W) in the Gulf of Chiriquí using SCUBA and an underwater hydraulic drill (Figures 2 and 7). Coral cores were cut perpendicular to density bands with a high-speed band saw and slabbed into 7-mm-thick slabs. The slabs were cleaned with deionized water and X rayed (35 kV, 3 Ma, 60-90 s) with a Phillips Radiflour medical X ray unit using Kodak X-OMAT-G X ray film. X ray contact positive prints are used to develop a chronology based on annual density bands and as a guide for sampling along the axis of maximum growth. Subannual samples for isotopic analysis were collected by low-speed drilling with a Dremel tool and carbide tipped dental drill bit at approximately 1-mm intervals along the axis of maximum growth. In places where the sampling transect was changed along a coral slab, overlapping samples were collected in order to ensure that no interval was missed. One to 3 mg of aragonite powder from each sample was prepared for isotopic analysis by vacuum roasting for 1 hour at 275°C. Samples are dissolved in 100% H_3PO_4 at 50°C: the resulting CO_2 gas was then analyzed with a VG Micromass 602E mass spectrometer upgraded with SIRA series electronics. The National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, NIST-20 standard was analyzed 2 to 3 times daily. A total of 2739 discrete samples were analyzed with 15% replication. The $\delta^{18}O$ is presented relative to PDB. For $\delta^{18}O$ the average standard deviation for replicate samples is 0.053‰, and for the 600 standards run is 0.067‰.

Singular Spectrum Analysis (SSA) was used to separate the significant oscillatory modes in the S1 $\delta^{18}O$ record using software written by E. Cook (Lamont Doherty Earth Observatory). The SSA program is based on methods outlined by *Fukunaga* [1970], *Vautard and Ghil* [1989], and *Vautard et al.* [1992].

S1 Chronology: 1707-1984

The S1 core spans 277 years from June 1984 to mid-1707 (Figure 7). The bottom several centimeters were discolored and had a spurious $\delta^{18}O$ signature and are not included in the final data set. The average sampling frequency was 9.9 samples/year and varied from 17 to 7 per year. The chronology was constructed by cross-checking the annual $\delta^{18}O$ variation (average 0.9‰) against the annual dense bands counted from the X ray positive prints. The COADS data indicate that El Niño events result in a 1° to 1.5 °C SST increase in the Gulf of Chiriquí. As will be shown, the S1 coral has preserved this signal as a 0.2-0.3‰ depletion in skeletal $\delta^{18}O$ for most, but not all of historically documented El Niño's [*Quinn et al.*, 1987, *Quinn*, 1992]. *Wellington and Glynn* [1983] observed that the low-density band in specimens of *Pavona spp.* is formed during the dry season (January through April) throughout the Pacific coast of Panamá. We have observed that low-density band formation in *Porites* occurs at the same time. Decreased cloud cover possibly triggers higher rates of photosynthesis in corals and greater extension rates. Dense bands formed during the wet season (from May to December) when ITCZ-related cloud cover is high and rains have lowered SSS. In the S1 coral the most depleted $\delta^{18}O$ values for each year coincide with an annual dense band, indicating that dense band formation occurs during the annual wet season. We used this relationship in constructing the chronology by setting the lowest $\delta^{18}O$ value in a given year equal to November. The height of the wet season occurs in October and November (Figure 3), and SSS measurements in the Gulf of Panamá show that the lowest salinities are found during September and October (Figure 4). We have assumed that the month of minimum SSS in the Gulf of Chiriquí has remained constant.

The S1 record from 1984 to 1799 is uninterrupted. However, an irregular core break exists at 1799 that is the result of a drilling hiatus. By correlating the $\delta^{18}O$ data with the very strong El Niños of 1790-1793 and 1782-1784 [*Quinn*, 1992], we have estimated that approximately 1 year is missing at this core break. The lack of significant dissolution and bio-erosion at the break, and the multiple "fits" with other El Niños back to the early 1700s support our interpretation of a missing year. For time series analysis the data from this missing year were artificially constructed by inserting average monthly values based on the chronology from 1799 to 1984. Before time series analysis the data set was interpolated to equal time increments of 10 per year, which approximately corresponds to the average sample density over the entire data set. We estimate that the final S1 $\delta^{18}O$ chronology back to 1707 is accurate to within ± 2 years.

Annual Calibration: 1950-1984

During coral growth the $\delta^{18}O$ of accreting carbonate varies with seawater temperature and isotopic composition. *Epstein et al.* [1953] determined that for every 1°C rise in water temperature the $\delta^{18}O$ of biogenic calcium carbonate decreases by 0.22‰. Although corals accrete aragonite which is several parts per mil depleted in ^{18}O relative to equilibrium values, the ^{18}O disequilibrium offset has been found to be constant within a coral genus [*Weber and Woodhead*, 1972] and along the axis of maximum growth [*Land et al.*, 1975; *McConnaughey*, 1986, 1989]. In areas with substantial SST changes, coral $\delta^{18}O$ records have been used to track ambient SST at subseasonal resolution [*Fairbanks and Dodge*, 1979; *Dunbar and Wellington*, 1981; *Weil et al.*, 1981; *Patzold*, 1984; *McConnaughey*, 1989; *Dunbar et al.*, 1994].

The $\delta^{18}O_{sw}$ also directly influences the $\delta^{18}O$ composition of coral skeletal aragonite [*Epstein et al.*, 1953; *Fairbanks and Matthews*, 1979; *Swart and Coleman*, 1980; *Dunbar and Wellington*, 1981; *Cole and Fairbanks*, 1990; *Cole et al.*, 1993]. Seawater $\delta^{18}O$ variations are small in most regions of the tropical ocean, but can be substantial where changes in evaporation, precipitation, or runoff cause pronounced seasonal and interannual changes. In areas where SST variations are small and/or well known, $\delta^{18}O$ time series in corals have been used to infer variability in $\delta^{18}O_{sw}$ [*Swart and Coleman*, 1980; *Cole and Fairbanks*, 1990; *Cole et al.*, 1993]. Thus, a key problem in interpreting coralline $\delta^{18}O$ data is determining the degree to which $\delta^{18}O_{sw}$ or SST changes are prevalent at the sample site.

Figure 8 shows the S1 $\delta^{18}O$ data from 1950 to 1984 plotted with COADS monthly SST data from 1950 to 1985, Panamá (Barro Colorado Island) monthly precipitation data from 1950 to 1985, and monthly $\delta^{18}O$ of Panama precipitation ($\delta^{18}O_{ppt}$)(Howard Air Force Base) data for 1969 to 1983 [*International Atomic Energy Agency (IAEA)*, 1969, 1970, 1971, 1973, 1975, 1979, 1983, 1986]. A striking feature of the coral $\delta^{18}O$ data is the large-amplitude regular oscillations that occur each year. The annual range in SST in the Gulf of Chiriquí is small and irregular (1-2°C) due to trade wind blocking by the mountains in Panamá. Variations in SST occur during El Niño events when water temperatures rise by 1 to 2°C in the Gulf of Chiriquí. Although high SSTs explain a portion of the S1 $\delta^{18}O$ signal, particularly during El Niño events, the strong annual $\delta^{18}O$ cycle in the coral is driven primarily by seasonal changes in rainfall and $\delta^{18}O_{ppt}$ that induce changes in $\delta^{18}O_{sw}$.

The ITCZ contributes to seasonal $\delta^{18}O_{sw}$ variability in Panamá via its regulation of rainfall patterns and $\delta^{18}O_{ppt}$. The monthly $\delta^{18}O_{ppt}$ monitored at Howard Air Force Base in Panamá from 1968 to 1983 has varied from -13.5 to 3.4‰ with an average annual variation of ~10‰ (Figure 8). The most depleted $\delta^{18}O_{ppt}$ values occur during the height of the wet

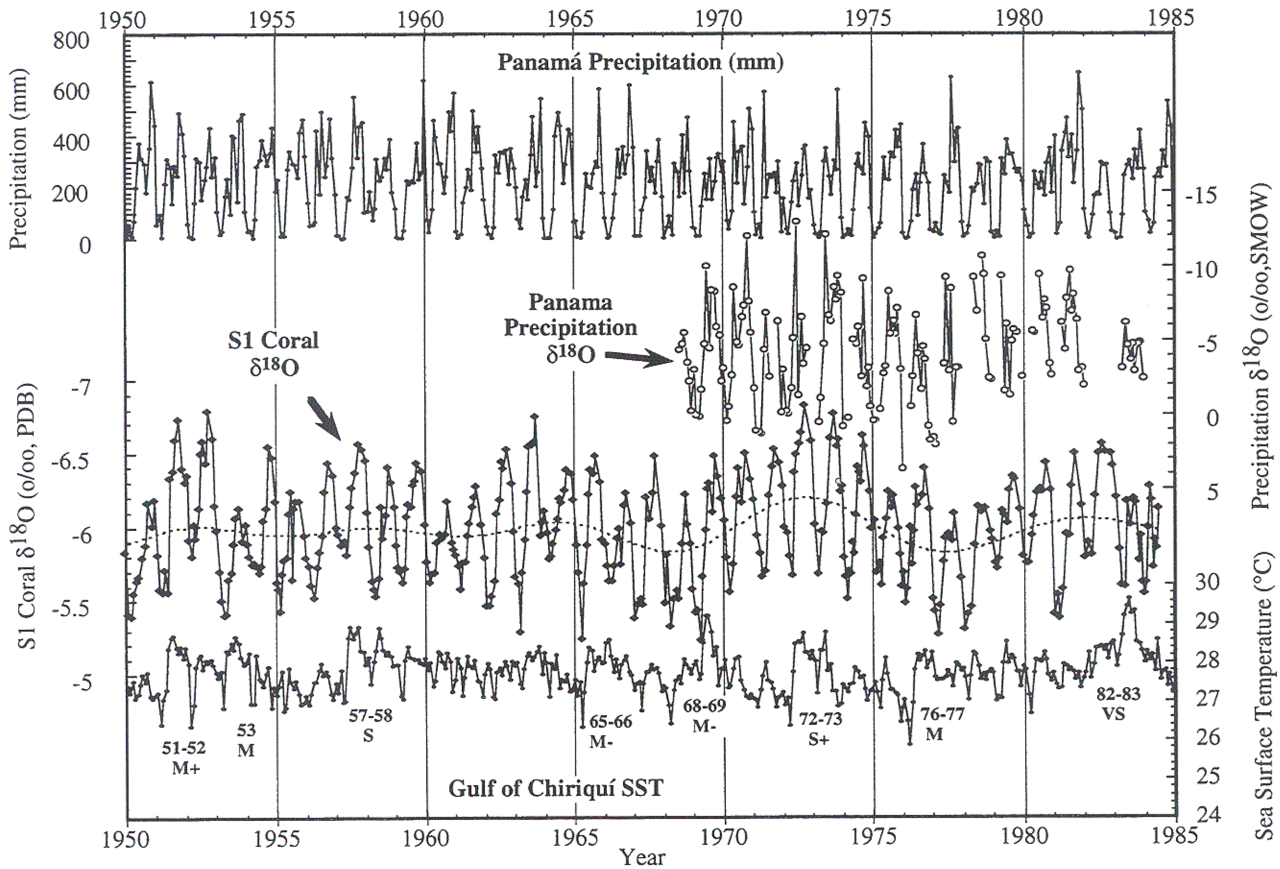

Figure 8. Comparison of S1 $\delta^{18}O$ (1950–1984), Gulf of Chiriquí sea surface temperature (SST)(1950-1985), Panama rainfall $\delta^{18}O$ ($\delta^{18}O_{ppt}$) from Howard Air Force Base (1968-1983), and Barro Colorado precipitation (1950-1985). The dashed line is the summation of reconstructed components (RCs) 1-6 and is used here to highlight the longer-period oscillations in S1 $\delta^{18}O$. El Niño events are indicated (VS, very strong; S, strong; M, moderate).

season when intense convective thunderstorms over Panamá produce precipitation with a $\delta^{18}O$ composition that ranges from -8 to -12 (°/oo, SMOW). A similar depletion in ITCZ wet season precipitation is observed at Ilopango, San Salvador, an area also strongly affected by the ITCZ [*IAEA* 1969, 1970, 1971, 1973, 1975, 1979, 1983, 1986]. Although the $\delta^{18}O_{ppt}$ data from Howard Air Force Base are discontinuous, there is a strong correlation with the S1 $\delta^{18}O$ data (Figure 8). To quantify this relationship, the $\delta^{18}O_{ppt}$ data were fitted with a cubic spline and missing monthly data interpolated from the spline. Wet and dry season coral $\delta^{18}O$ values from 1968 to 1982 were calculated by averaging the two consecutive months with recorded maximum (and minimum) values. The same procedure was used for $\delta^{18}O_{ppt}$. A least squares linear regression of the wet and dry season extreme values is shown in Figure 9. The linear relationship between the S1 $\delta^{18}O$ (PDB) and Panamá $\delta^{18}O_{ppt}$ (SMOW) is

$$\delta^{18}O_{ppt} = 47.99+8.72(\delta^{18}O_{coral}) \quad r=0.89 \qquad (1)$$

When the same correlation procedure is applied to the product of monthly rainfall (mm), $\delta^{18}O_{ppt}$, and S1 $\delta^{18}O$ an r value of 0.83 is obtained. Due to the inability to resolve exact months within a year in the coral chronology, and the lack of data for many months in the $\delta^{18}O_{ppt}$ record, lower r values result when 3-month averages or raw data were correlated. It should also be noted that the $\delta^{18}O_{ppt}$ and precipitation records are from single stations, whereas the S1 coral $\delta^{18}O$ is representative of a larger area. This may explain some discrepancies in the records.

The seasonal $\delta^{18}O_{ppt}$ changes within a given year are likely influenced by "the amount effect" as described by *Dansgaard* [1964] or by the source of the water vapor. During times of

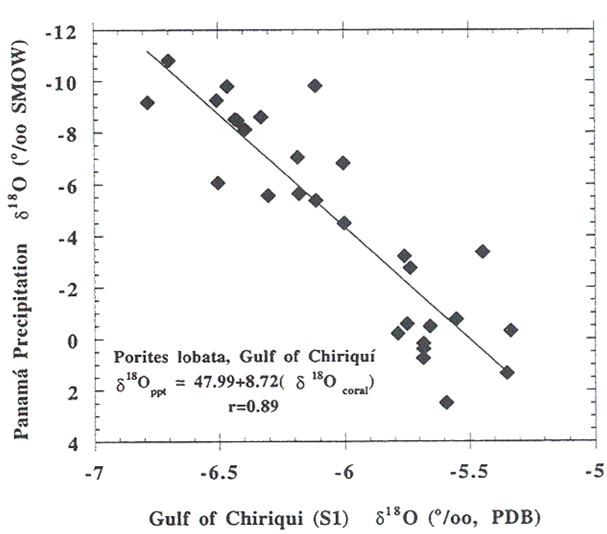

Figure 9. Least squares correlation of maximum and minimum values in a given year for S1 $\delta^{18}O$ and Howard Air Force Base $\delta^{18}O_{ppt}$. The r -value of the linear correlation equals 0.89.

intense rainfall the $\delta^{18}O_{ppt}$ is more depleted than that of moderate rainfall events because a larger fraction of the cloud's water vapor precipitates. Under intense rainfall conditions, $\delta^{18}O_{ppt}$ will approach -11 to -12‰, which is the initial composition of cloud vapor in the tropical Pacific [*Craig and Gordon,* 1965]. In their survey of coastal and island stations, *Gat and Gonfiantini* [1981] identified Panamá as one region in which rainfall $\delta^{18}O$ is more depleted than the general trend due to the amount effect. The source of much of the moisture precipitated over Panamá is also potentially a cause of the annual $\delta^{18}O_{ppt}$ range. The NE trade winds which cross Panamá pick up moisture from the Caribbean Sea and tropical western Atlantic and transport it into the ITCZ. However the relative salinity and $\delta^{18}O$ stability of the Caribbean over the annual cycle in relation to the 10‰ annual $\delta^{18}O_{ppt}$ range in Panamá strongly suggest that the source of the $\delta^{18}O_{ppt}$ annual cycle is related to seasonal influx of convective rainfall associated with the ITCZ.

The large annual $\delta^{18}O_{ppt}$ and salinity range in coastal Panamá are sufficient to account for the majority of the S1 $\delta^{18}O$ seasonal cycle. In equatorial Atlantic surface waters, *Craig and Gordon* [1965] calculated a $\Delta\delta^{18}O_{sw}/\Delta SSS$ slope of 0.11. Based on salinity and seawater $\delta^{18}O$ measurements in the Gulf of Panamá, *Dunbar and Wellington* [1981] calculated that $\Delta\delta^{18}O_{sw}/\Delta SSS = 0.12$. *Dunbar and Wellington* [1981] also calculated that 70% of the annual $\delta^{18}O$ signal in corals from the Gulf of Panamá was due to the annual SST variation of ~4-6°C and 30% due to SSS variations. Although the Gulf of Panamá SSS data are from the pier at the Pacific entrance to the Panamá canal (Figures 2 and 4) and therefore do not necessarily reflect conditions in the Gulf of Chiriquí, a similar annual range of 5 to 11‰, as previously discussed, is expected for the Gulf of Chiriquí [*Bennett,* 1966]. The number and average annual discharge of rivers which empty into the Gulf of Chiriquí are equal to or greater than in the Gulf of Panamá [*Hall et al.,* 1992]. Using the relationship derived by *Dunbar and Wellington* [1981], an average annual salinity variation of 6‰ in the Gulf of Chiriquí would result in a 0.72‰ $\delta^{18}O$ signal in corals. Based on the SSS and PPT data for Panamá, this estimate is reasonable and indicates that roughly 80% of the 0.9‰ average annual $\delta^{18}O$ range in the S1 coral is due to SSS fluctuations. The irregular annual SST range of 1°C would explain another 0.22‰, as the effects of SSS and SST on $\delta^{18}O_{sw}$ at this site are additive. During extreme El Niño events, the COADS data indicate that SST warms an additional 1 to 2°C in the Gulf of Chiriquí.

The S1 $\delta^{18}O$ data record most, but not all historically documented ENSO events. Some strong (S) and very strong (VS) El Niño events identified by *Quinn et al.* [1987] and *Quinn* [1992] are not associated with $\delta^{18}O$ anomalies in the S1 coral $\delta^{18}O$ record. Other weak (W) and medium (M) strength events have left a large $\delta^{18}O$ signature in the S1 coral. For example, although some strong events are recorded such as the 1972-1973 and 1951-1952 El Niños (Figure 8), other severe events like 1982-1983 are not apparent. As reported by *Glynn* [1983, 1990], corals in the Gulf of Chiriquí bleached in early 1983 as a response to elevated SSTs. The S1 $\delta^{18}O$ record appears truncated at this time as SSTs abruptly rose to near 30°C. We believe that the attenuated $\delta^{18}O$ signal during 1982-1983 indicates that the S1 coral stopped accreting skeleton for several months and may have bleached. The possibility exists that other times of extreme El Niño SST anomalies also influenced coral growth in the S1 coral. However, *Dunbar et al.* [1994] report that based on a 367-year coral record of SST changes in the Galápagos, the 1982-1983 El Niño appears to have been unique in magnitude since at least 1586. It is possible that coral records of ENSO may not always match *Quinn et al.'s* [1987] and *Quinn* 's [1992] records of relative ENSO strengths because of the inherent problem of working with sparse or misleading historical records, particularly beyond the range of instrumental data.

In summary, large seasonal salinity and $\delta^{18}O_{ppt}$ fluctuations in the Gulf of Chiriquí due to ITCZ-related precipitation and runoff account for ~80% of the annual variability in the S1 $\delta^{18}O$. Irregular annual SST variation explains the other 20% of the variance. Past El Niño events are not always recorded at S1 which may be a function of the relatively small magnitude of the SST signal in comparison to the large annual SSS change.

Interannual and Decadal Changes in S1 Oxygen Isotopes

The S1 $\delta^{18}O$ data set from 1984 to 1707 (n =2739) is shown in Figure 10. The reconstruction reveals both regular seasonal and interannual oscillations. SSA was used to separate the significant oscillatory modes and aid in interpretation of the data. Summations of three sets of reconstructed components (RCs) from the SSA results (discussed below) are also shown in Figure 10 and serve to highlight variance at periods ≥ 9 years.

SSA is a fully nonparametric analysis technique based on principal component analysis of delay coordinates in vector space for a time series. Thus it is ideally suited for the analysis of short, chaotic time series. SSA uses M-lagged copies of a centered time series to calculate eigenvalues and eigenvectors of their covariance matrix. RCs and empirical orthogonal functions associated with variance greater than the average variance are extracted at discrete frequencies and ranked according to the percent variance they account for in the original series. The period of each RC is determined by calculating the average cycle length for an individual RC over the entire time series. SSA isolates in time intermittent oscillations, the shape of which are determined adaptively from the data. This is different from classical spectral analysis, where basis functions are prescribed sines and cosines. SSA permits detailed reconstructions of any subset of significant components in the time series. The RCs describe the change in amplitude of an eigenvector over the length of the time series and can be used to filter the data without having to normalize the series. SSA results are strongly influenced by the selected window length (M). M values that are too small will cause neighboring peaks in the spectrum to coalesce, and large choices of M (high resolution) will split peaks into several components with neighboring frequencies. *Vautard et al.* [1992] show that SSA is unable to isolate peaks at frequencies lower than $1/M$ (periods > M). For the S1 data, SSA was run multiple times at different values of M. Values of M between 15 and 40 years did not significantly change the results, whereas M >40 years subdivided close frequencies, and M <15 years grouped frequencies. As the majority of clear oscillations in S1 $\delta^{18}O$ had periods less than 20 years we set M at 25 years. The application of SSA to paleoclimatic time series is discussed by *Vautard and Ghil* [1989] and *Vautard et al.* [1992]. For examples of the application SSA to time series analysis, see *Ghil and Vautard* [1991], who applied SSA to a 135-year-long global-surface-temperature time series, and *Rasmusson et al.* [1990] who showed that the irregular ENSO phenomenon contains a rather regular quasi-biennial signal.

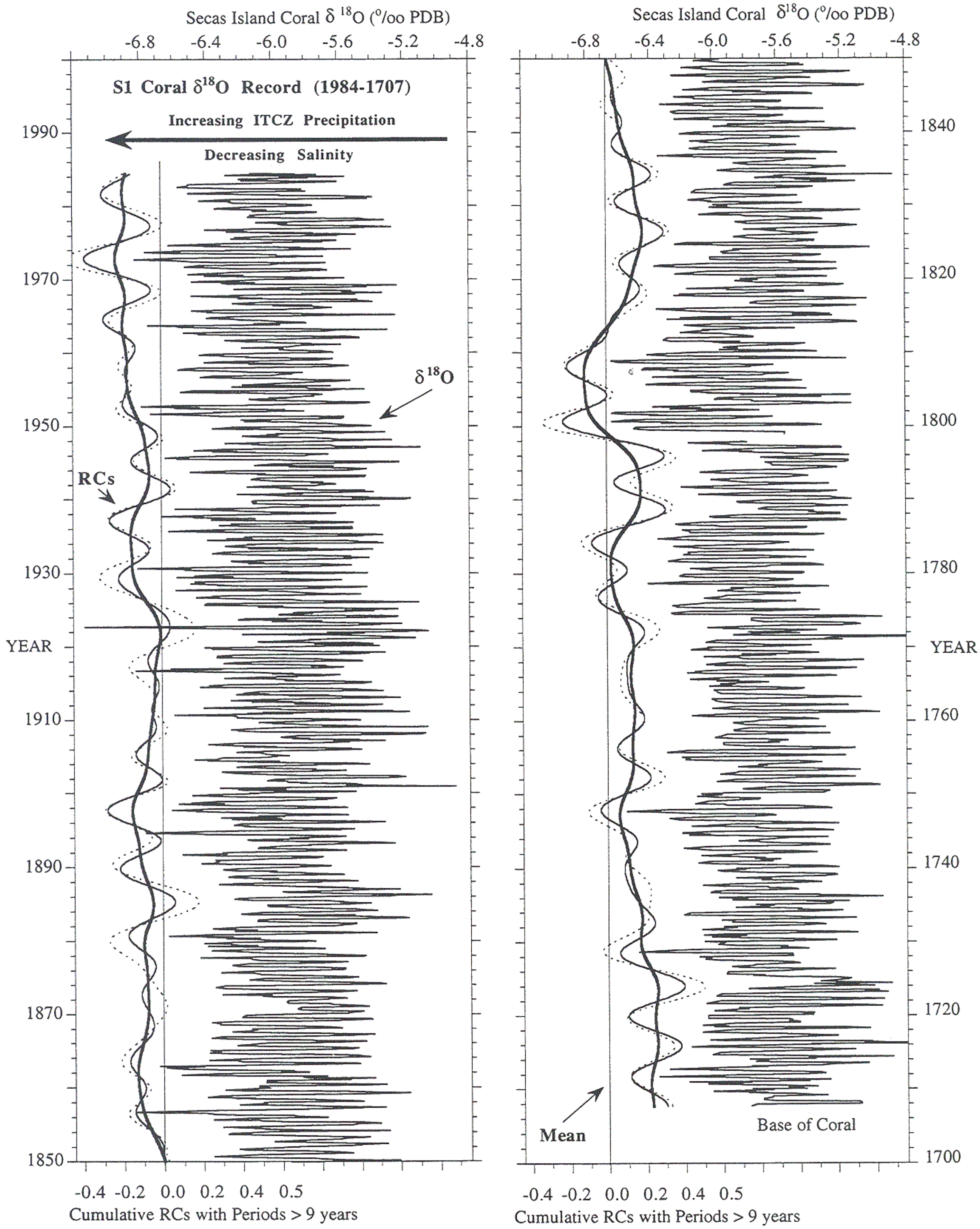

Figure 10. Secas Island (coral core S1) $\delta^{18}O$ (PDB) data showing both pronounced annual and decadal-scale variability. Left panel, 1850-1984; Right Panel, 1707-1850. The left-most curves in each panel are cumulative reconstructed components (RCs) with periods ≥ 9 years from Singular Spectral Analysis (SSA) (RCs 1-2; lower frequency bold line, RCs 1-4; solid line; RCs 1-6; dashed line). The RCs serve to highlight the interannual and decadal-scale oscillations in the raw $\delta^{18}O$ data.

Table 1a. Singular Spectrum Analysis: Unfiltered S1 $\delta^{18}O$ Series 1707.7 -1984.4

Eigenvector	Period, years	Variance percentage	Cumulative Variance percentage
1,2	1	51.1	51.1
3	trend	8.4	59.5
5,6	9	4.5	64.0
4	27-33	2.8	64.0
9,10	5-6	2.4	69.2
7	18-20	1.9	71.1
8	11	1.7	72.8

S1 $\delta^{18}O$ (n =2767), M=25 years (data not filtered).

Table 1b. Singular Spectrum Analysis: S1 $\delta^{18}O$ Data Filtered 1707.7 -1984.4.

Eigenvector	Period, years	Variance percentage	Cumulative Variance percentage
1,2	9.1	43.9	43.9
4,5,7,8,9	3 to 7	29.8	73.7
3	17	17.8	91.5
6	33	7.2	98.7

S1 $\delta^{18}O$ (n =2767), M=25 years (data filtered at 2 years and detrended).

SSA results are presented for the unfiltered data and for a high-pass filtered series. The 10 most significant eigenvectors for each analysis, their periods and percent variance are listed in Tables 1a and 1b. In the results for the unfiltered data (Table 1a) the first 10 eigenvectors account for 72.8% of the total variance in the time series. The annual cycle (average 0.9‰) accounts for 51% of the total variance. The dominance of the annual $\delta^{18}O$ cycle attests to the regularity of the seasonal nature of climatic forcing in this region. A long-term -0.4‰ $\delta^{18}O$ trend is also a significant component of total variance (8.4%).

To more closely examine the interannual and interdecadal periods clearly manifest in the S1 record, the analysis was repeated once the trend (RC 3, Table 1a) was subtracted from the centered time series and a smoothing spline filter was applied that removed periods ≤ 2 years. The results of this analysis are presented in Table 1b. With the annual cycle and long-term trend removed, nine eigenvectors had variance greater than the average. The first two eigenvectors have an average period of 9 years and explain 44% of the variance in the filtered time series. Other interannual increases in variance occur in the ENSO band at 2-7 years (30%), near 17 years (17%), and near 33 years (7%). The magnitude of the variations in $\delta^{18}O$ range from 0.2 to 0.6‰. The first several decadal $\delta^{18}O$ oscillations are apparent in Figure 8. Similar oscillations do not occur in Gulf of Chiriquí or Gulf of Panamá SST. However comparison of S1 $\delta^{18}O$ from 1965 to 1985 with $\delta^{18}O$ from a specimen of *Pavona gigantea* collected from Uraba Island in the Gulf of Panamá [*Druffel et al.*, 1990] reveals a striking fit of the long-term trends (Figure 11). Uraba is situated within 5 km of the entrance to the Panamá canal in the ITCZ rainfall belt (Figure 2). The Uraba $\delta^{18}O$ record has nearly twice the annual range as the S1 coral due to the much larger annual SST range in the Gulf of Panamá. The similarity of decadal $\delta^{18}O$ trends preserved in nearshore settings in both the gulfs of Chiriquí and Panamá strongly suggests that the cause of the variability in coral $\delta^{18}O$ and thus $\delta^{18}O_{sw}$ is regional in nature and has synchronously affected coastal waters all along Panamá's Pacific coast.

We conclude that decadal oscillations in the S1 $\delta^{18}O$ record are not related to SST changes and must therefore be related to variations in $\delta^{18}O_{sw}$ which are directly related to ITCZ precipitation. Although the fit of the decadal trends in the S1 $\delta^{18}O$ and Panamá $\delta^{18}O_{ppt}$ is not perfect and the length of the overlapping records is too short for statistical analysis, the maximum and minimum values of $\delta^{18}O_{ppt}$ track the trend in

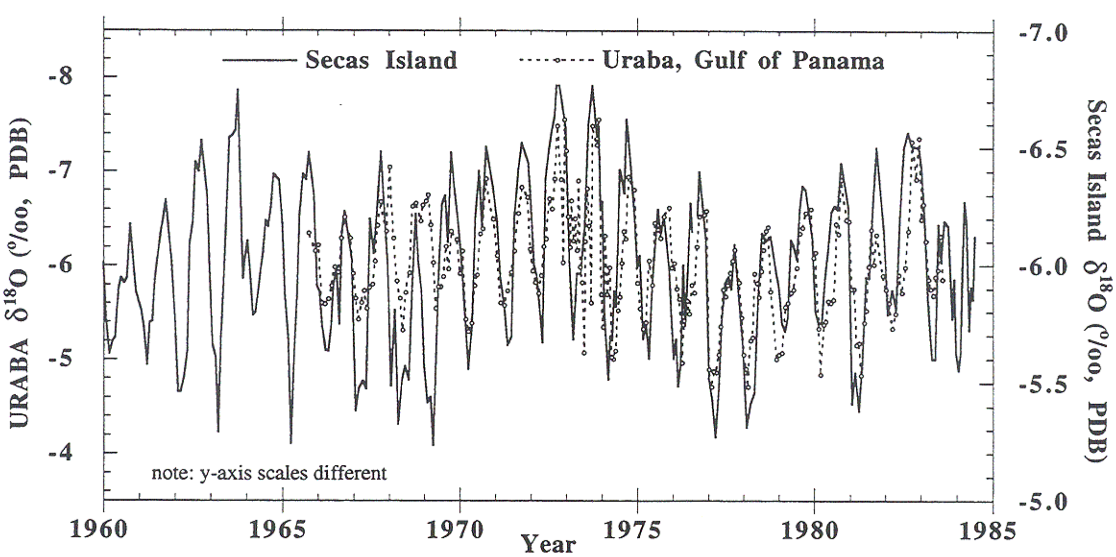

Figure 11. S1 $\delta^{18}O$ compared to $\delta^{18}O$ from Uraba in the Gulf of Panamá (Uraba data from *Druffel et al.*, 1990; for location see Figure 2). The agreement of the long-term changes in the mean from both sites demonstrates that the interannual trend is a regional feature affecting at least the entire nearshore Pacific coast of Panamá.

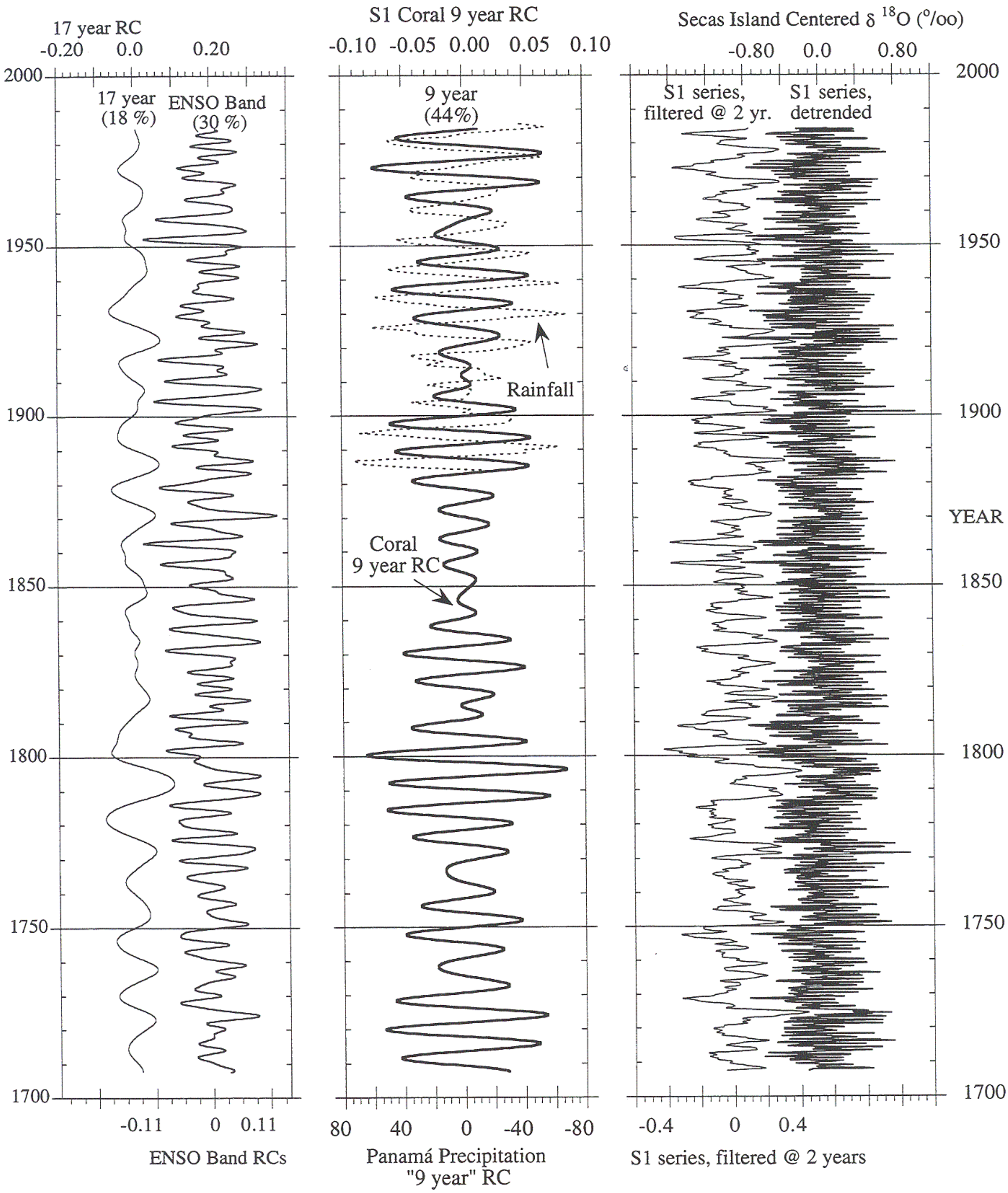

Figure 12. Time evolution plot of the three interannual reconstructed components (RCs) that account for the most variance when the S1 $\delta^{18}O$ record was detrended and high-pass filtered, removing periods < 2 years. The original detrended series and 2-years filtered series are shown in the right panel. An in phase 9-year component also exists in a two station averaged annual Panama precipitation record from 1986 to 1884.

coral $\delta^{18}O$ and indicate a correlation. Correspondence of the S1 and Uraba $\delta^{18}O$ records with Panamanian $\delta^{18}O_{ppt}$ indicates that the decadal trend is a regional feature and suggests that it is related to long-term changes in the rate of convection in the ITCZ or $\delta^{18}O$ of the source moisture. To further fine tune the S1 calibration, direct measurements of SSS, $\delta^{18}O_{ppt}$, and $\delta^{18}O_{sw}$ are needed in the Gulf of Chiriquí.

Discussion of Significant Frequency Components

Although the annual migration of the ITCZ dominates seasonal rainfall patterns throughout the low-latitude tropics, little is known about its long-term behavior over timescales of decades to centuries. The strong linkage and modulation of the ITCZ at interannual scales by ENSO make analysis of the ITCZ a complex problem in southeast Asia and in most of the tropical central Pacific. Outside this region the seasonal movements of the ITCZ are more easily decoupled from ENSO. In the Gulf of Chiriquí the unique combination of relative thermal stability and large annual precipitation-induced salinity change has resulted in an ideal location to monitor seasonal and decadal changes in precipitation patterns and the ITCZ using corals.

An important feature of the ITCZ is the latitudinal range of the annual migration. Current climate models do not accurately simulate the seasonal variation in the ITCZ [*Philander,* 1990; *Senior and Mitchell,* 1993]. The annual variations in S1 $\delta^{18}O$ throughout the 277-year time series account for 51% of the total variance (Table 1a). The rainfall data indicate that many wet seasons contain two rainfall peaks (Figures 6 and 8). However, at no time in the last 65 years has the zone of maximum rainfall in the ITCZ moved completely north of Panamá, producing two distinct wet seasons within a year, separated by a period of drought. Although the S1 $\delta^{18}O$ record does not resolve monthly rainfall events, it agrees with the seasonal timing of the precipitation data and places important constraints on the latitudinal variations of the ITCZ back to 1707. Over the past 277 years (Figure 10) the northward expansion of the rainfall maximum associated with eastern Pacific ITCZ appears to have always resulted in a single pronounced wet season in Panamá, suggesting that the rainfall maximum associated with the ITCZ's most northern position has never moved well to the north of Panamá. Conversely, the S1 record indicates that the ITCZ has always moved as far north as Panamá at least back to the early 1700s. These conclusions can be confirmed by independent dating of the base of the coral. The current chronology attests to the regularity of the ITCZ annual movements and reflects the magnitude and apparent consistency of the seasonal cycle. Furthermore, the 1 year reconstructed component of the S1 data (not shown) and the detrended $\delta^{18}O$ series (Figure 12) demonstrate that the average seasonal change in coral $\delta^{18}O$ during and after the end of the Little Ice Age was relatively constant, suggesting that eastern Pacific rainfall seasonality was relatively unchanged across this climatic transition.

S1 $\delta^{18}O$ variability at interannual and decadal periods is at least regional in scale and related to long term changes in salinity and/or $\delta^{18}O_{ppt}$. A time evolution plot of the three prevalent interannual frequencies derived from SSA analysis of the detrended and filtered S1 $\delta^{18}O$ record (Table 1b) reveals variations in amplitude of the dominant periods over the length of the record (Figure 12).

Table 2. Singular Spectrum Analysis: Annual Panamá Precipitation (Gamboa; 9°7'N, 79°42 W, and Christobal; 9°22'N, 79°52'W).

Eigenvector	Period, years	Variance percentage	Cumulative Variance percentage
1,2	3.5	15.2	15.2
7,14,15	<3	11.3	26.5
11,12,13	9.4	11.1	37.6
5,6	4.6	9.2	46.8
4,8	14-15	9.1	55.9
3	trend	6.8	62.7
9	22	4.2	66.9
10	7.8	3.8	70.7

Two station average precipitation (1884-1986, M=30 years).

Although the S1 coral $\delta^{18}O$ time series does not record all ENSO events, many ENSO events are recorded. Panamá is generally dryer than normal during an El Niño [*Ropelewski and Halpert,* 1987; *Deser and Wallace,* 1990]. Conditions also tend to be wetter than normal the summer before an El Niño and dryer than normal during the late fall-early winter following an El Niño [*Kiladis and Diaz,* 1989]. SSA results of average annual precipitation totals from two Panamá stations (Gamboa and Christobal) [*Windsor,* 1990] covering the period 1884 to 1986 are listed in Table 2. Strong ENSO band variability occurs in Panamanian precipitation that is lacking in the S1 $\delta^{18}O$ record (see Tables 1a and 1b). A total of 24% of variance in Panamá precipitation occurs in the ENSO band with 15.2% at a period of 3.5 years and 9.2% at a period of 4.6 years. The fact that S1 $\delta^{18}O$ has a relatively minor ENSO component results from the opposing influence of SST and precipitation during El Niño events. In Panamá the general reduction of precipitation during El Niños [*Ropelewski and Halpert,* 1987; *Kiladis and Diaz,* 1989] has the opposite effect on coral $\delta^{18}O$ as the higher SSTs. This effect may explain the small component of ENSO band variability preserved in the S1 coral.

In the S1 coral the "ENSO" component of $\delta^{18}O$ variability shows a decrease in amplitude from 1920 to 1930 and again in the 1820s. Currently, there are only two long coral records of ENSO variability in the Pacific. In the Galápagos, *Dunbar et al.,* [1994] found an increase in the long period component of ENSO before 1750. This change is not apparent in the S1 data, although the record may be too short for rigorous comparison. At Tarawa in the Central Pacific, *Cole et al.* [1993] using a 96-year coral record, found an increase in the 5-6 component of ENSO from 1930 to 1950 with little change in the 1920s. More coral records from the Pacific will be required to evaluate changes in ENSO variance over time.

The 9-year component in S1 $\delta^{18}O$ may be related to precipitation variability in Panamá . Although, the recurrence interval of ENSO ranges from 2 to 10 years [*Trenberth,* 1976; *Julian and Chervin,* 1978], the low frequency component is very irregular [*Philander,* 1990] and cannot account for the 9-year RC. However, eleven percent of the variance in Panamá precipitation occurs at a period near 9 years (Table 2). A 9-year period also exists in a monthly precipitation record from Barro Colorado Island that extends from 1925 to 1987. The 9-

year RC of annually averaged Panamá precipitation from 1986 to 1884 is shown in Figure 12. The precipitation 9-year RC consistently leads the coral 9-year RC by ~2 years. This same lead is observed in the monthly precipitation. The length of this lead time is problematic, as a slight 2 to 3 month lead would have been expected if the 9 year variation in precipitation was influencing salinity and $\delta^{18}O_{sw}$ in the Gulf of Chiriquí. The 2 year lead could be indicative of a chronology offset in the coral, however the top 100 years of the coral chronology is more certain and we favor an environmental cause for the two year lead. We note that a 9-year period is also one of several interannual and interdecadal components found in global surface air temperatures spanning the last 135 years [*Ghil and Vautard,* 1991], although the connection to the ITCZ is not clear. Variations in the heat content of the tropics could influence both the rate of convection and the mean position of the ITCZ [*Philander,* 1990].

In order further evaluate the dominant coral 9-year component, the bandwidth of the 9-year RC was estimated. SSA was used to quantify the variance in 100 year segments of the S1 $\delta^{18}O$ time series that were offset by 30 years. The resulting spectra, estimated by maximum entropy for periods from 6 to 15 years, are shown in Figure 13. In SSA output, RC periods are calculated by averaging over the entire time series. The 9-year RC is thus an average period. The overlapping 100-year segments reveal that the dominant interannual period has actually varied from 7.5 to 11.8 years. The large increase in variance near 6.5 years in the 1824-1924 segment is most likely related to ENSO. In the segments from 1794-1894, 1824-1924, and 1854-1954, a strong increase in variance occurs in the 11-year range. This is also the average period of the solar sunspot cycle. It is tempting to relate the strong interannual variability in S1 $\delta^{18}O$ cyclicity to changes in solar irradiance related to the sunspot cycle. *Friis-Christensen and Lassen* [1991] found a strong relationship between northern hemisphere land temperature and the length of the solar cycle. They calculated that the solar cycle varies from 9.8 to 11.8 years. The bandwidth of the S1 9-year RC is within this range. However, time evolution plots of sunspot number and modeled solar irradiance [*Foukal and Lean,* 1990] and the S1 $\delta^{18}O$ 9-year RC do not correlate, shifting both in-phase and out-of-phase over the length of the time series. Additionally, there is no widely accepted mechanism to explain a relationship between small changes in solar irradiance and climate. *Hunten et al.,* [1991] argue that only subtle atmospheric variations related to solar irradiance have been observed at altitudes of 30 km or higher. However, increases in variance near 11 years have been observed in other climatic time series. *Labitzke and van Loon* [1988] and *van Loon and Labitzke* [1988] report an association between the solar cycle and the quasi-biennial oscillation (QBO) and *Barnett* [1989] observed the same effect on SSTs. *Dunbar et al.* [1994] report 11-year and 22-year cyclicity in growth band thickness and annual $\delta^{18}O$ in a 370-year coral record from Urvina Bay in the Galápagos Islands. The proxy SST record from Galápagos is strongly influenced by ENSO and is consistent with solar cycle modulation of ENSO and the QBO [*Barnett,* 1989]. *Tinsley and Heelis* [1993] further develop a potential mechanism for a solar-climate linkage involving atmospheric electricity and cloud microphysics that was outlined by *Tinsley and Deen* [1991]. They argue that the solar wind affects electrostatic charging of supercooled water droplets and aerosols at the tops of clouds, which increases the rate of ice nucleation. This, in turn, influences latent heat release and vertical motions in the atmosphere with the most pronounced effects seen under summer conditions. Although this mechanism is controversial, it highlights the potential importance of clouds associated with the ITCZ.

The source of increased variance at an interannual period near 17 years is also problematic. SSA of 100-year, 30-year offset segments of the S1 record indicates that the period of this component varies from 16.7 to 19.6 years. An 18.6-year period to the nutation of the Earth's rotational axis has been predicted by *Borisenkov et al.* [1983, 1985] to result from lunar gravitational attraction. Based on model outputs of changes in solar irradiation due to nutation, they concluded the effects would be most evident at polar latitudes. The low latitude of the Gulf of Chiriquí combined with the lack of agreement between the S1 18.9-year RC and *Borisenkov et al.'s* [1985] plots of annual mean variations in insolation resulting from the orbital perturbations leads us to conclude that the period near 18.9 years in S1 must be due to other unrelated and unknown causes. However, we note that *Dunbar et al.* [1994] report increased variance in both coral $\delta^{18}O$ and growth band thickness at a period between 17.5 and 18 years in their Galápagos record.

The long-term trend in the S1 $\delta^{18}O$ is most apparent in Figure 10 as a shift of -0.4‰ over the length of the record. The majority of the shift occurred around 1850, before which $\delta^{18}O$ was generally higher. Two mechanisms could account for this change: a 1°-2°C reduction in SST or a reduction in precipitation associated with a southward displacement of the ITCZ. Several multicentury coral-based reconstructions from Cocos Island and Champion Island (Galápagos) are currently under development, which will be used to further constrain past changes in the ITCZ and its relationship to regional SST variations.

In summary, SSA indicates that interannual variability in the S1 $\delta^{18}O$ record is concentrated at periods near 9, 3-7 (ENSO band), 17, and 33 years. The period of the dominant interannual 9-year RC varies from 7.5 to 11.8 years. The first interdecadal coral $\delta^{18}O$ oscillation is strongly correlated with a coral $\delta^{18}O$ record from the Gulf of Panamá, suggesting the interannual variations are regional features affecting the entire west coast of Panama. There is a strong 9-year component of variance in Panamá rainfall, suggesting some connection to the S1 $\delta^{18}O$ record. Based on the annual and interannual relationship of S1 $\delta^{18}O$ to ITCZ precipitation, we interpret the interannual changes as longer-term variations in $\delta^{18}O_{sw}$ and/or precipitation amount. This interpretation suggests that small but significant interdecadal changes in ITCZ-related precipitation have occurred in the eastern Pacific since at least the early 1700s.

Conclusions

1. A 277-year subseasonal $\delta^{18}O$ record from a Gulf of Chiriquí coral has resulted in the first subseasonal resolution reconstruction of ITCZ variability. Calibration of the $\delta^{18}O$ data with SST, SSS, $\delta^{18}O_{ppt}$, and PPT data from Panamá indicates that ~80% of the 0.9‰ annual cycle is the direct result of changes in the $\delta^{18}O_{sw}$ due to the influx of ^{18}O-depleted precipitation during the summer rainy season. The annual cycle dominates the variance throughout the S1 record, accounting for 51% of total variance, attesting to the

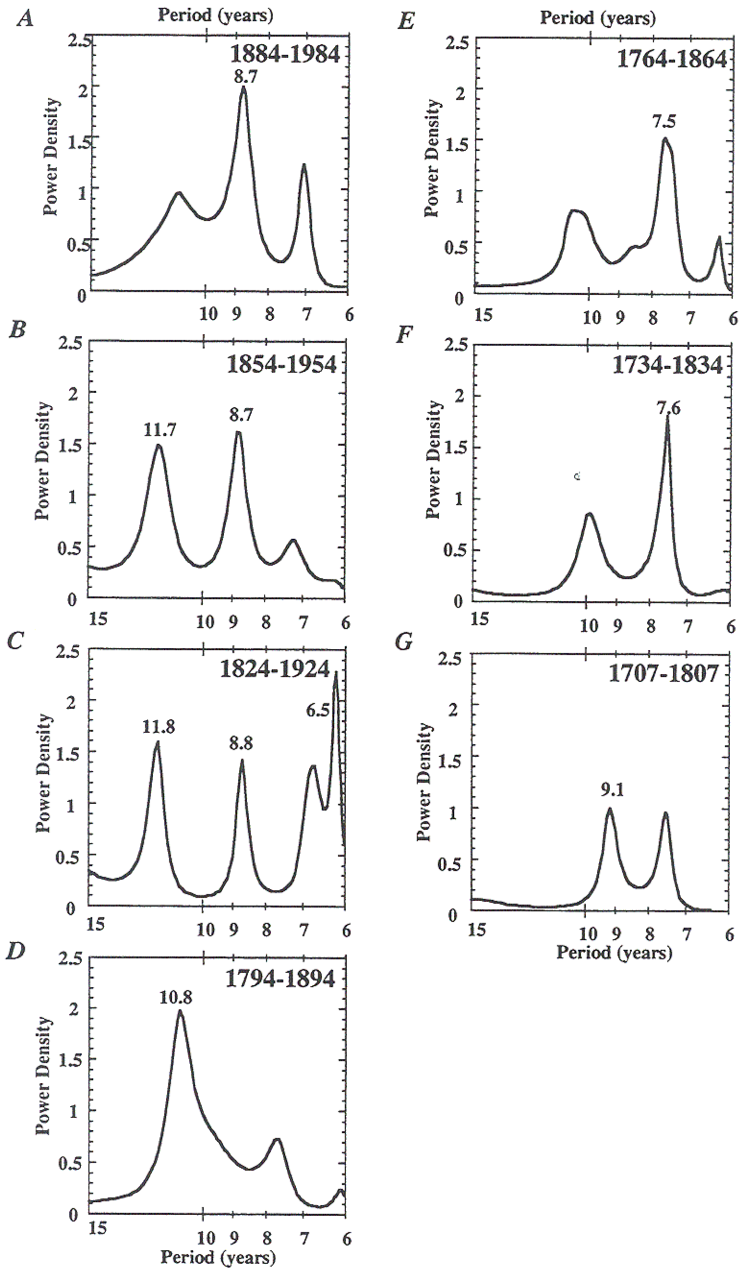

Figure 13. SSA spectra estimated by maximum entropy for periods from 6 to 15 years for seven 100-year segments of S1 $\delta^{18}O$ time series that were offset by 30 years: (a) 1884-1984, (b) 1854-1954, (c) 1824-1924, (d) 1794-1894, (e) 1764-1864, (f) 1734-1834, and (g) 1707-1807. Unlike spectra calculated by the Blackman-Tukey method, the significance of spectral peaks is not proportional to peak height. The significant peaks indentified by SSA analysis are labeled with the average period for that interval. The overlapping 100-year segments reveal that the dominant interannual period in the S1 coral $\delta^{18}O$ time series has actually varied from 7.5 to 11.8 years.

regularity of the north-south migration of the eastern Pacific ITCZ over the past three centuries.

2. This reconstruction places constraints on the range of the annual latitudinal range of the eastern Pacific ITCZ back to 1707. Over the past 277 years the northward expansion of the rainfall maximum associated with eastern Pacific ITCZ appears to have always resulted in a single pronounced wet season in Panamá, suggesting that the ITCZ has never been positioned far to the north of ~8°-10°N. Conversely, the S1 record indicates that the ITCZ has always moved as far north as Panamá at least back to the early 1700s.

3. Interannual and decadal oscillations occur throughout the $\delta^{18}O$ record. During the last 20 years the first major long-term cycle also occurs in a coral $\delta^{18}O$ record from the Gulf of Panamá and in $\delta^{18}O_{ppt}$ data from Panamá. This indicates that long term changes in the S1 coral $\delta^{18}O$ are regional features related to fluctuations in ITCZ rainfall and/or $\delta^{18}O$ content of precipitation.

4. In the Gulf of Chiriquí the latter part of the Little Ice Age is expressed as a series of large-amplitude $\delta^{18}O$ oscillations that we interpret as evidence for changes in the amount of ITCZ-precipitation in Panamá. The similarity of average

seasonal change in S1 $\delta^{18}O$ during and after the Little Ice Age suggests that the eastern Pacific ITCZ annual cycle was relatively unchanged during the LIA, but that interdecadal changes were stronger.

5. Singular Spectrum Analysis (SSA) indicates that interannual increases in variance in the Gulf of Chiriqui coral $\delta^{18}O$ time series occur near periods of 9, 3-7 (ENSO band), 17, and 33 years. A strong in-phase 9-year period in Panamá precipitation suggests a possible relationship between the 9-year component observed in the coral and the ITCZ. The period of the dominant 9-year RC varies from 7.5 to 11.8 years. This band encompasses the 11-year solar cycle. However, due to the lack of correlation with sunspot number and modeled solar irradiance, our single site reconstruction of the ITCZ does not support a direct link between solar insolation variability and tropical climate.

6. This seasonal-resolution coral record of ITCZ variability from the Gulf of Chiriquí, Panamá suggests that the eastern Pacific ITCZ varies on interannual timescales. The possibility that the ITCZ, the dominant mode of seasonal variability in the tropics, contributes to interannual variability has been suggested by *Philander* [1990]. This suggestion was based on observations that interannual fluctuations, the seasonal cycle, and mean conditions are all influenced by similar interactions between the ocean and the atmosphere. From an atmospheric point of view, movements of the ITCZ follow the zone of maximum SSTs, moving northward when SSTs near the equator start to fall. However, from an oceanographic perspective the northward migration of the ITCZ causes the SE trades to intensify, resulting in upwelling and cooler SST near the equator. *Philander* [1990] suggests that other factors such as seasonal heating of the continents and interactions of the ocean and the atmosphere may affect movements of the ITCZ. This idea can be tested by determining whether annual, interannual, and decadal variability in the eastern Pacific ITCZ is more than regional in scale through comparison with other seasonal-resolution paleoclimatic records from locations within the ITCZ.

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