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Stable oxygen isotopic composition of corals from the Gulf of Guinea as indicators of periods of extreme precipitation conditions in the sub-Sahara

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Abstract. Stable oxygen isotopic analyses of scleractinian coral skeletons from the Gulf of Guinea in the eastern Atlantic reveal that the corals from this region can be used to identify periods of severe drought and above average precipitation in sub-Sahara Africa. Data presented in this paper show an inverse correlation between precipitation in the Sahel and the $\delta^{18}O$ values of a coral skeletons of the species *Siderastrea spp.* collected from the island of Principe in the Gulf of Guinea. This is opposite to the correlation expected, as previous work has suggested that higher sea surface temperatures occur in the Gulf of Guinea during periods of low rainfall in the Sahel. Such an association would lead to a positive correlation between Sahel precipitation and skeletal $\delta^{18}O$. The explanation for the observed inverse correlation is that the salinity of the Gulf of Guinea is strongly influenced by the outflow from the Niger and Congo rivers. These periods of high freshwater input also correlate with periods of higher rainfall in the sub-Sahara and therefore affect the $\delta^{18}O$ values of the coral skeleton. The correlation between $\delta^{18}O$ values of the coral skeleton and temperature in the northern subtropical Atlantic Ocean (r= -0.34), the magnitude of the dipole (r= -0.45), and the latitudinal position of the intertropical convergence zone (r= -0.37) illustrate that the $\delta^{18}O$ values in the coral skeleton reflect climate dynamics of the region that affect the precipitation patterns in sub-Sahara Africa.

1. Introduction

A coral-based reconstruction of tropical Atlantic climate variability seems desirable and feasible, because tropical Atlantic sea surface temperature (SST) and rainfall over the surrounding land areas are statistically associated and because coral-based variables respond to SST and salinity, both climatically sensitive parameters. Research shows that dry conditions have persisted in the sub-Sahara since the late 1960s [*Lare and Nicholson*, 1994], while over the same period, NE Brazil (north of 10°S) has seen higher than average rainfall [*Nobre and Shukla*, 1995; *Hastenrath and Greischar*, 1993]. These long-term changes are modulated by shorter 10-to 13-year fluctuations that are coherent with similar fluctuations in SST patterns. Other empirical and modeling studies have confirmed the association between Atlantic SST and sub-Saharan precipitation anomalies [*Folland et al.*, 1986; *Citeau et al.*, 1989; *Lamb and Peppler*, 1992; *Janicot*, 1994]. However, because of strong interdecadal to multidecadal character of the Atlantic variability, the lack of complete, long-term SST and climate records for the west African region has hampered the investigation and detection of statistically significant relationships over extended time periods. In order to extend the climate record beyond the reach of instrumental data, we have investigated the use of proxy indicators of climate based on coral skeletons collected from the Gulf of Guinea.

A number of studies [*Weare*, 1977; *Houghton and Tourre*, 1992; *Enfield and Mayer*, 1997] have shown that tropical SST anomalies (SSTA) are dominated by two large characteristic regions of variability north and south of the Atlantic Intertropical Convergence Zone (ITCZ). These patterns can be approximated by the covariability (contours and shading) of SSTA with simple averages over the two rectangular areas shown in Figure 1. The indices formed by averaging SSTA over these rectangles are referred to as tropical North Atlantic Ocean (NATL) and tropical South Atlantic Ocean (SATL), respectively [*Enfield*, 1996]. Anomalous heating in either region alone is associated with a movement of the ITCZ in that direction and influences ITCZ-related rainfall accordingly. During times when the two indices are of opposite sign, the tropical Atlantic is said to be in an antisymmetric, or "dipole" configuration, and the climatic effects on nearby land regions are most highly punctuated. The difference between these indices (NATL minus SATL) is itself an index of dipole intensity. Whether dipole configurations occur randomly or in response to some systematic large-scale interaction, is not well understood. They tend to be infrequent and statistically insignificant at periodicities of less than about 7 years (the anticorrelation between them is marginal), though when they occur their climate impact is impressive [*Moura and Shukla*, 1981; *Nobre and Shukla*, 1996]. The dipole variability becomes more energetic and significant in the 10-to 20-year interdecadal band [*Mehta and Delworth*, 1995] and may be associated with prolonged climate anomalies, such as extended droughts in sub-Saharan NW Africa.

The fortuitous location of the Gulf of Guinea site (Figure 2) within the SATL SST pattern, and near or on perennially traveled ship tracks, provides us with a unique opportunity to develop coral

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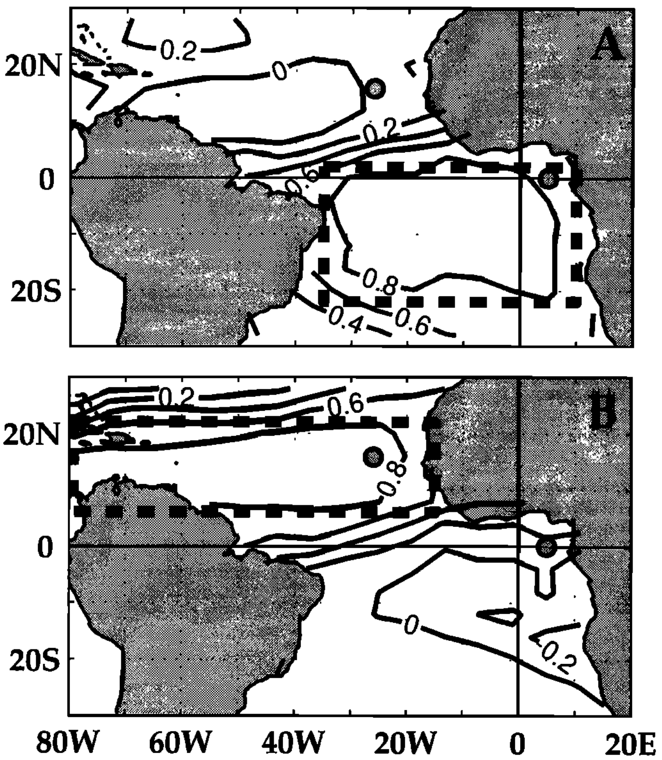

Figure 1. (a) Distribution of correlation (contours, in tenths) between gridded SSTA and a regional index of SSTA (shaded rectangular area) in the tropical South Atlantic Ocean (SATL). (b) As in (Figure 1a) but for the tropical North Atlantic Ocean (NATL).

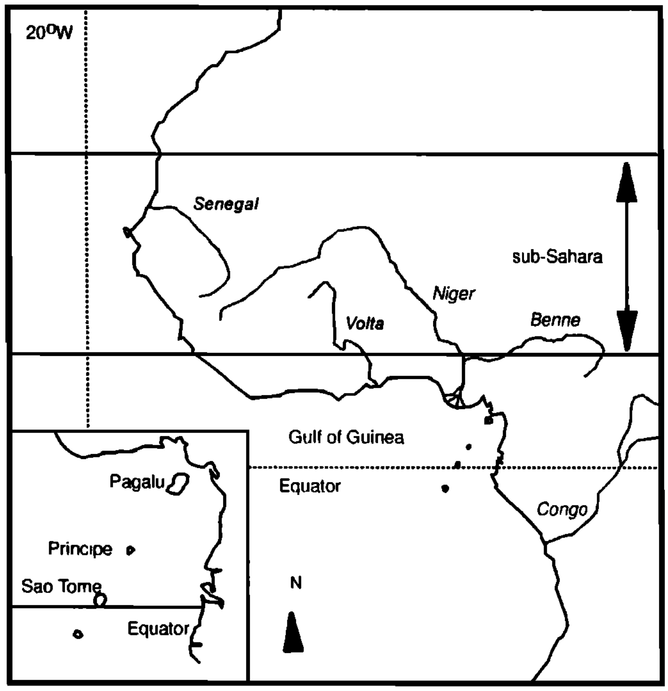

Figure 2. Map showing the location of Sao Tome and Principe in the Gulf of Guinea. The region between 11°N and 18°N is the approximate extent of the sub-Saharan region.

chronologies as proxies for large-scale SST variations and SST-related land climate over periods that transcend instrumental records. The Sao Tome-Principe Islands lie on or near the 60% covariance contours for local SSTA versus the SATL index (based on seasonal averages). In other words, the local SST surrounding the islands has a correlation of about 0.8 with the large-scale area indices that are significant for climate variations over large land areas of the western hemisphere [*Enfield*, 1996]. To the extent that salinities near the islands are related to nearby land climate (through local rainfall or continental runoff), the coral response to salinity may also be useful as a more direct index of regional climate behavior (Figure 3). In the Gulf of Guinea, salinity is most likely a proxy for runoff from the Niger and Zaire Rivers, which drains a large basin north of the Guinea coast. The influence of runoff on the salinity patterns can be seen in mean salinity data for the region [*Levitus*, 1986] (Figure 3).

For this paper, stable oxygen isotope, density, and fluorescence analyses were conducted on a coral skeleton of the species *Siderastrea spp.* collected from the island of Principe in the Gulf of Guinea to determine their chronologies and how well they record SST and salinity changes. The particular coral analyzed has a 65-year record extending back to 1928. The results from the Principe coral are discussed in detail, along with their relationships with SST and runoff data, to illustrate how the use of corals in the Gulf of Guinea can be used as indicators of extreme precipitation conditions in the sub-Saharan region of Africa.

2. Background on the use of Corals as Proxy Indicators of Climate

Scleractinian corals can live for hundreds to thousands of years. The large massive calcareous skeletons produced by these corals have characteristics that are very useful to geologists, geochemists, climatologists, and environmental scientists in reconstructing coral growth rates and paleoenvironments. These characteristics include (1) alternating bands of high- and low-density skeletal material, where each pair of high- and low-density bands represent approximately 1 year's growth and (2) the carbon and oxygen stable isotope composition of the skeletal material. Sclerochronology, based on the assumption of annual periodicity of the high- and low-density band pair, has been used alone to date past environmental conditions, which have resulted in increased or decreased growth rates in corals [e.g., *Dodge and Vaisnys*, 1975; *Weber et al.*, 1975; *Hudson et al.*, 1976; *Schneider and Smith*, 1982, *Dodge and Lang*, 1983]. Sclerochronology has also been used in combination with other signals recorded in the skeleton to investigate episodes of river

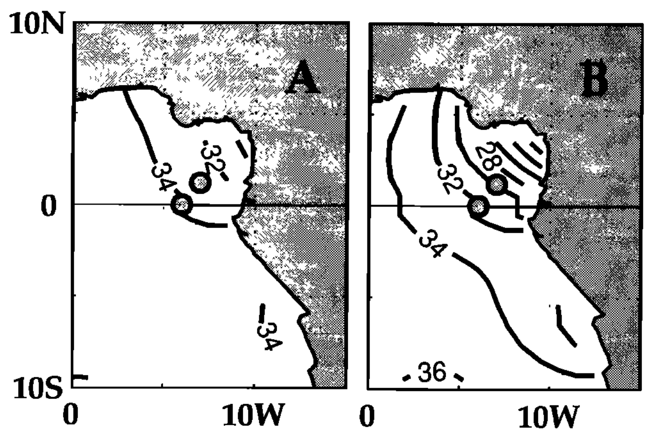

Figure 3. Salinity variations in the Gulf of Guinea. Data represent seasonal averages in per thousand (data from *Levitus* [1986]),(a) September salinity and (b) December salinity.

runoff that leave fluorescent bands in the skeleton [*Isdale*, 1984], pollution events [*Dodge et al.*, 1984, *Dodge and Gilbert*, 1984], or mixing rates of the ocean from bomb-derived C-14 [*Druffel*, 1982, 1987], temperature and paleosalinity records using oxygen isotopes [*Fairbanks and Dodge*, 1979; *Cole and Fairbanks*, 1990; *Patzöld*, 1992], and insolation and productivity records using carbon isotopes [*Fairbanks and Dodge*, 1979].

Fluorescence is a form of luminescence and is the emission of light from a material when excited by visible and ultraviolet radiation. *Isdale* [1984] discovered that coral skeletons emit yellow-green fluorescence when irradiated with ultraviolet light. The fluorescence is thought to be caused by increased concentrations of humic and fulvic acids derived from the degradation of plant materials and so can be used as an indicator of freshwater, terrestrial runoff [*Boto and Isdale*, 1985; *Isdale and Kotwicki*, 1987].

3. Methodology

3.1. Coral Collection

Several hemispherical heads of corals approximately 30 cm in diameter were collected from the island of Principe in the summer of 1993. Of these, a specimen of *Siderastrea spp.* from Principe (P2) was analyzed in detail. This coral was collected from Ponta Banana on the north coast of Principe in water 4 to 6 m deep. This coral has a record extending back 65 years to 1928 [*White*, *1995*] (Figure 4).

3.2. Densitometry

Coral slabs approximately 3 mm thick were cut using a diamond saw. Each slab was X rayed and the annual pairs of low- and high-density bands identified. Densitometry transects of the digitized image of each X radiograph were made perpendicular to the density bands and converted to skeletal density [*Chalker and Barnes*, 1990].

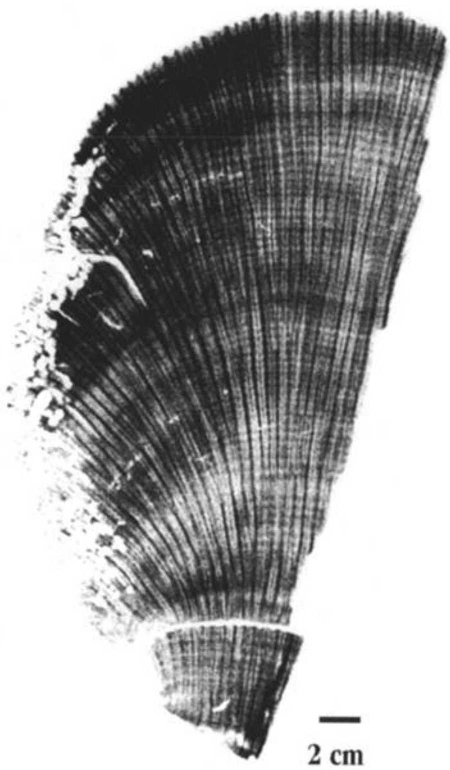

Figure 4. X radiograph of *Siderastrea spp.* from Principe used in this study.

3.3. Stable Isotope Analyses

The corals were slabbed and mounted on glass slides for isotopic sampling. The samples of coral skeleton for stable isotope analysis were taken using a computer controlled microsampling dental drill. Each sample represented a 320-μm–long section of a continuous transect of the coral. The sample was drilled and the powder transferred to a reaction vessel using a scalpel. The drill and the work area were cleaned with a brush and forced air between each sampling event. Tests have shown that the computerized drilling system does not affect the coral composition [*Swart and Leder*, 1995].

The powdered coral samples were run without pretreatment using an automated carousel attached to a Finnigan-MAT 251 mass spectrometer. Isotopes are corrected using the procedures of *Craig* [1957] modified for a triple collector mass spectrometer. Data are quoted relative to PDB according to the conventional notation.

3.4. Fluorescence Analysis

The fluorescence of each coral was determined by the use of a pulsating laser developed by *Milne and Swart* [1994]. A low-powered, sealed-plasma-cartridge, pulsed nitrogen laser (λ_{ex}=337 nm) was used as an excitation source. The laser pulses are coupled into a fiber optic bundle by means of a fused-silica lens mounted on a fiber coupler. A fused-silica, SMA-terminated, fiber optic bundle is made up of a central excitation fiber surrounded by six collection fibers at the sensing end. The collection fibers are arranged linearly at the receiving end and are matched to the entrance slit of a small in-line monochromator of the Fastie-Ebert design. A UV-enhanced silicon photocell with an integral operational amplifier circuit was used to detect luminescent emission light carried back through the fiber optic bundle. A quartz window mounted in the fiber optic positioner allows monitoring of the intensity of individual laser pulses. An intensity normalization signal is obtained by monitoring the surface reflection from the quartz window with a second silicon photocell.

The fiber optic bundle is held rigidly at a defined distance above the surface of the coral slab. A linear positioning rail table under stepper motor control was used to move the coral slab underneath the sensor end of the fiber optic bundle. The coral can be moved in increments as small as 25.5 μm. The increment size used in these analyses was 127.5 μm. The fluorescence data are reported in relative units and are normalized to the mean of each transect.

3.5. Climate Data Sources

For large-scale SSTA indices, we used data from the 1950-1992 monthly maps from *Smith et al.* [1996] reconstructed from the Comprehensive Ocean-Atmosphere Data Set (COADS [*Woodruff et al.*, 1987]), averaged over the SATL and NATL regions after removing the monthly climatological distributions. The dipole index is calculated as the NATL minus the SATL. To obtain a local measure of SSTA in the vicinity of Sao Tome and Principe, we extracted the time series of monthly COADS SST for the nearest 2°x2° grid box (7925) for the years 1928 to 1940 and 1950 to 1993. As an index of the meridional motions of the ITCZ, we calculate the monthly averaged divergence of the COADS wind velocity along 29°W and estimate by interpolation the latitude of minimum (most negative) divergence. The data set of NW African precipitation is comprised of area-averaged annual precipitation anomalies determined by *Nicholson* [1994] for five regions of the sub-Sahara. Data for precipitation over the Niger and Zaire basins are similarly derived for five degree squares from the data of *Bigot et al.* [1995] (Figure 5a).

4. Results

4.1. Density

Monthly density values for the Principe coral P2 have a range of 1.41 to 1.91 g/cm^3. From 1965 to 1985 there is a gradual increase in the density value from values during 1945 to 1965. Thereafter a gradual decrease between 1985 and 1993 occurs. The range in values for the years 1976 to 1982 and 1986 to 1993 are similar, from 1.5 to 1.69 g/cm^3. Between 1983 and 1985 the density values drop to within the range of 1.4 to 1.55 g/cm^3. Variations in the annual mean values are shown in figure 5b.

4.2. Fluorescence

The fluorescence values obtained from the coral skeleton are highest during the 1930s and from 1947 to 1959. The values begin to decrease in 1962 and culminate in the lowest values that occur from 1970 to 1973. The values fluctuate during the rest of the record, but remain lower than the values for the first half of the century (Figure 5c).

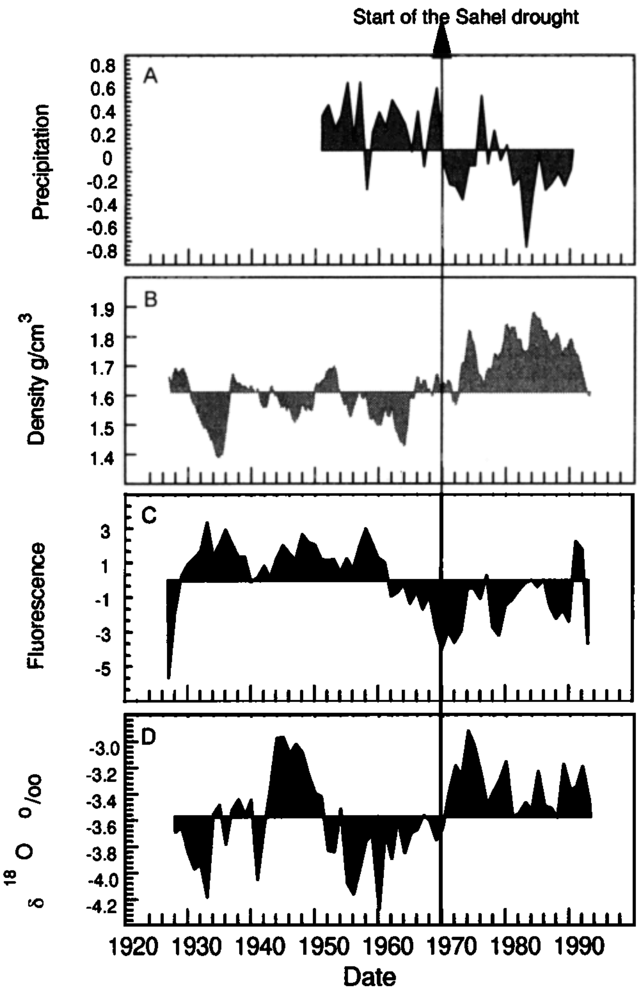

Figure 5. A comparison of (a) precipitation data from the Zaire and Niger river basins [*Bigot et al*, 1995], (b) density data from the Principe coral, (c) fluorescence data from the Principe coral, and (d) oxygen isotopic data from Principe. All data are annual means.

4.3. Stable Oxygen Isotopes

Values for $\delta^{18}O$ from the Principe coral skeleton P2 range from -5.77 to -2.75 ‰ (Figure 6). These values are most negative during the years 1952 to 1958 and more positive during the years 1942 to 1951 and the years 1971 to 1981. Variations in the annual oxygen isotopic composition are shown in Figure 5d. Carbon isotopic variations are shown in Figure 6 but are not correlated significantly with any environmental variables.

4.4. Data Correlations

Correlation values for all of the data relationships, calculated on the annual averages of the data, are shown in Table 1. Values in parentheses indicate correlations significant at the 95% level. Significant correlations occur between annual $\delta^{18}O$ averages for the Principe coral and the NATL (r= -0.41), the Atlantic SST dipole (r= -0.45), the position of the ITCZ (r= -0.37), and sub-Saharan precipitation (r= -0.33). Fluorescence from the coral correlates negatively with annual averages of SST for the region (r=-0.42) and with annual averages of density for coral (r=-0.33) and correlates positively with Sub-Sahara precipitation (r=0.37).

5. Discussion

5.1. Sub-Sahara of West Africa

The sub-Saharan zone extends between approximate latitudes of 11° and 18°N, from Mauritania, Senegal, and Gambia in the west to Niger and Nigeria in the east (Figure 2). This zone is a transition area between the essentially rainless Sahara desert to the north and an area of more abundant rainfall to the south [*Lamb and Peppler*, 1991]. Eighty percent of the year's rainfall occurs during July to September. Small amounts of rainfall occur in May, June, and October [*Lamb and Peppler*, 1991].

Much of the rainfall in this region comes from squall lines and easterly waves [*Burpee*, 1972]. Squall lines form from the West African Disturbance Lines, a system of a long line of active thunderstorms [*Hastenrath*, 1991]. Easterly waves form from the African easterly jet [*Lare and Nicholson*, 1994], also called the West African Mid-tropospheric Jet [*Hastenrath*, 1991].

Rainfall has declined significantly in the sub-Sahara West Africa since approximately 1970. Extremely deficient rainy seasons, 1972, 1977, and 1983-1984, were all the culmination of progressive rainfall decrease during several preceding years. Rainfall was close to the 1941-1982 average during the years 1959-1967, abundant during the years 1950-1958, and varied during the years 1941-1949 [*Lamb and Peppler*, 1991].

5.2. Atlantic Sea Surface Temperature and Precipitation in the Sub-Sahara SST Patterns

Through several empirical studies, *Lamb* [1978a, b] recognized a distinctive pattern of SST anomalies that was associated with drought years in the sub-Sahara (Figure 1). The SST anomaly pattern is made up of anomalously cool water to the northwest of a line between West Africa and northeast Brazil and anomalously warm water to the

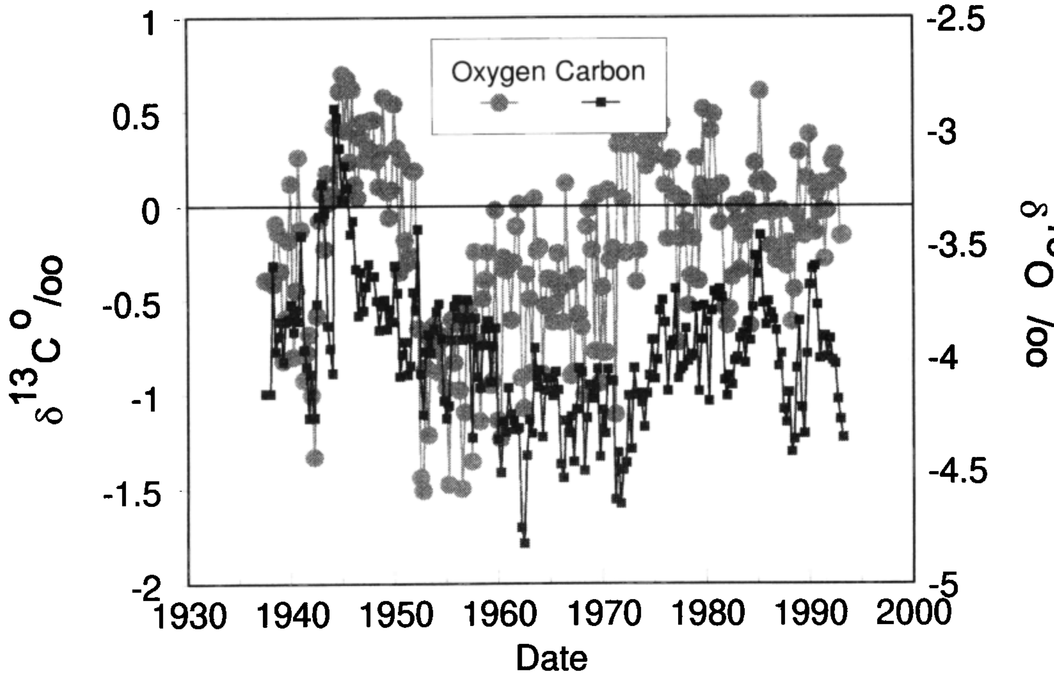

Figure 6. Oxygen and carbon isotopic data from the Principe coral interpolated to a frequency of four samples per year. Sampling of the coral was conducted at a rate of one sample every 300 μm which represented a sampling rate of between 4 and 10 samples a year.

southeast of that line. This pattern in the Atlantic is often accompanied by similar features in the tropical Pacific consisting of cool water to the north of 5 N and warm water to the south of 5 N. The Indian Ocean is dominated by positive anomalies at such times [*Lamb,* 1978a, b; *Lamb and Peppler*, 1991; *Hastenrath,* 1984]. There are also associated southward displacements seen in surface pressure, wind field, and zones of maximum rainfall frequency and cloudiness anomalies during many drought years [*Lamb and Peppler,* 1992]. *Lamb* [1978a, b] and *Lamb and Peppler* [1991] found that this tropical Atlantic SST anomaly pattern tended to evolve or exist prior to the rainy season for 1968, 1972, 1977, and 1984.

Table 1. Regression Coefficients Between the Various Relevant Parameters Discussed in the Text

	R	S	O	F	D	SA	NA	Di
S	(+0.66)							
O	(-0.47)	(-0.33)						
F	+0.31	(+0.37)	-0.19					
D	(-0.55)	(-0.48)	+0.29	(-0.33)				
SA	(-0.45)	(-0.60)	+0.30	(-0.42)	(+.35)			
NA	+0.09	+0.11	(-0.41)	-0.03	-0.01	+0.04		
Di	+0.30	(+0.48)	(-0 45)	+0.24	-0.14	(-0.79)	(+0.53)	
IT	(+0.21)	(+0.34)	(-0.37)	+0.06	-0.12	(-0.44)	(+0.63)	(+0.74)

Regression coefficients between the various relevant parameters discussed in the text (S, Sahel: O, $\delta^{18}O$: F, Fluorescence; D, Density: SA, SATL: NA, NATL: Di, Dipole· IT, ITCZ). Coefficients which are statistically significant at the 95% confidence limits are shown in brackets.

Several numerical-empirical studies have examined the observations made by *Lamb* [1978a, b], *Lamb and Peppler* [1991, 1992], and *Hastenrath* [1984]. For the tropical Atlantic sector, these studies mainly support their findings [*Hastenrath,* 1991]. *Adedoyin* [1989] found that during the period of July, August, and September, the South Atlantic and Indian Ocean SST anomalies are negatively correlated with the amount of precipitation in Nigeria. He also found that the North Pacific and the North Atlantic SST anomalies are positively correlated with Nigerian rainfall. *Semazzi et al.* [1988] found that for the years 1970 to 1984, sub-Saharan rainfall significantly correlates with tropical Pacific and Atlantic SST anomalies. Their simulations run with the Goddard Laboratory for Atmospheres general circulation model (GCM) showed similar results.

Folland et al. [1986], *Palmer* [1986], and *Owen and Folland* [1988] conducted experiments with the U.K. Meteorological Office 11-level atmospheric general circulation model to examine the influence of SST on rainfall in the sub-Sahara. They found that SST anomalies in the Atlantic Ocean had an effect on rainfall in the sub-Sahara, but that SST anomalies in the global ocean had a larger effect. *Folland et al.* [1986] also found that the southern hemisphere and the northern Indian Ocean were warmer during drier periods in the sub-Sahara. The results of *Owen and Folland* [1988] results show that SST seems to be the main influence causing differences in rainfall in the sub-Sahara between a wet year, 1950, and a dry year, 1984.

5.3. Corals as Indicators of Extreme Rainfall Conditions in the Sub-Sahara

Originally, we postulated that there should be a positive correlation between the $\delta^{18}O$ of the corals skeletons and precipitation in the Sahel as during the drought years, the SST in the Gulf of Guinea is 1 to 2 C warmer than normal [*Lamb and Peppler,* 1991].

However, between 1928 and 1993 there no statistically significant correlation between SATL and $\delta^{18}O$ (r=0.30). The absence of a significant correlation between SATL and $\delta^{18}O$ suggests that the $\delta^{18}O$ signal in the coral skeletons from the Gulf of Guinea is not principally related to temperature. Furthermore the absence of such a correlation cannot result from variations in local precipitation as the highest precipitation occurs during warmer years and should actually enhance the normal inverse correlation between $\delta^{18}O$ and temperature. An explanation for this discrepancy can be found in the salinity data for the Gulf of Guinea [*Levitus*, 1986]. These data indicate that the area is significantly influenced by outflow from the Niger (Figure 3). Using the mean rainfall of 5 x 5 squares in the Niger basin [*Bigot et al.*, 1995] as an indicator of the amount of discharge from the Niger, there is a correlation of -0.47 (statistically significant at the 99% confidence limits) between the oxygen isotopic composition of the Principe coral and the rainfall in the Niger basin. This correlation agrees with the observed data and suggests that although Gulf of Guinea SST should be higher than normal during periods of Sahel drought, the signal is being overwhelmed by river discharge which itself is inversely correlated with the drought. Hence periods of drought in the Sahel are associated with higher salinities in the Gulf of Guinea and heavier oxygen isotopic compositions. These values occur in spite of higher temperatures and increased local rainfall in the Gulf of Guinea during the drought years.

The fluorescence record of the Principe coral also supports the notion that there have been periods of high freshwater input into the Gulf of Guinea waters. The fluorescence and the $\delta^{18}O$ values for the Principe coral generally are inversely correlated except for a few years in the mid-1940s. There is a positive correlation between the annual mean fluorescence and the sub-Sahara precipitation anomalies (r= 0.45). The relationships between the Principe coral $\delta^{18}O$ values, the sub-Saharan precipitation, and the Principe coral fluorescence suggests that the $\delta^{18}O$ values in the coral are affected by freshwater input to the waters around Principe. When there is more freshwater input to the Principe waters, the $\delta^{18}O$ values are more negative, and there is high rainfall in the sub-Sahara. When there is less freshwater input to the Principe waters, the $\delta^{18}O$ values are more positive, and there is a poor wet season in the sub-Sahara. Thus there is evidence that both SST and freshwater inputs to the Gulf of Guinea have affected the $\delta^{18}O$ values of the Principe coral and their relationship with the sub-Saharan precipitation anomalies.

6. Conclusions

The $\delta^{18}O$ of the coral skeleton from Principe is inversely correlated with precipitation over the Niger and Zaire river basins. Precipitation over these basins is positively correlated with precipitation in the Sahel region of Africa and hence the $\delta^{18}O$ of the coral skeleton is positively related to the magnitude of the Sahel drought. This observation suggests that the influence of salinity overwhelms the temperature influence on the oxygen isotopic composition of corals as during Sahel drought conditions the temperature of the Gulf of Guinea increases. The skeletal $\delta^{18}O$ also shows an inverse correlation with NATL, but no correlation with SATL. The larger negative correlation between the dipole and skeletal $\delta^{18}O$ compared to the correlation between $\delta^{18}O$ and NATL implies an added effect of the SATL which has the opposite sign with respect to NATL. This is consistent with the expectation that rainfall will be more affected when NATL and SATL are opposite. Under this condition the position of the ITCZ is either positioned towards the north (positive values of the dipole) or towards the south (negative dipole values). Positive dipole values therefore lead to increased precipitation in the Sahel and negative values lead to drought conditions. It is neither consistent with the direct effect of local SSTA or the larger SATL region with which local SSTA is correlated.

Inverse correlations between the Principe coral $\delta^{18}O$ and sub-Saharan precipitation are strongest during the 1950s when there was plentiful rainfall in the sub-Sahara and during the early 1970s when there was the most severe drought. Therefore corals collected from Principe in the Gulf of Guinea can best be used to indicate periods of extreme precipitation conditions in the sub-Sahara.

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