C. PROJECT DESCRIPTION

1. Results from Previous NSF Support

Swart and Dodge

Swart OCE-8900095 ($160K)/OCE-9217993 ($180K); Dodge OCE-9121344 ($29,715)/OCE9218508 ($101,000): The control of banding and C&O isotopic compositions in Scleractinian coral Skeletons: An experimental approach; P.K. Swart, A. Szmant, R. Dodge (NOVA Southeastern); Duration 3-1-89 to 3-1-97

Scleractinian corals were grown in the field under controlled and natural conditions for periods of 1.5 to 2 years. Physiological (photosynthesis, respiration, calcification) and environmental (temperature, light, salinity, isotopic composition of the water) variables were measured. At the end of the experiment, the isotopic composition of the coral skeleton was determined and the density patterns analyzed. These results have produced an improved understanding of stable isotopic fractionation in corals. A second experiment was conducted between 1992 and 1995. Results of this work are being completed and will be published in a series of four papers authored by Dodge, Swart, Szmant and Porter.

Papers:

Abstracts: Nine Abstracts

Swart _CLIMATE DYNAMICS ($25K) The investigation of stable isotopic records from corals in the Gulf of Guinea for paleoclimatic reconstruction: Duration 1-1-93 to 1-1-94

Amount

A speculative award was made to investigate whether corals suitable for paleoclimate analysis were present in the Gulf of Guinea. The result of this award was that three persons visited the islands of Sao Tome and Principe and collected a large number of 50 to 80 year corals. Collection of larger corals was not possible as a result of infrastructure problems.

Theses:
- White, K. 1995. Proxy indicators of climate in corals skeletons used to identify correlations between climate variations in the Gulf of Guinea and Subsaharan drought, M.S. thesis, University of Miami

1.0 INTRODUCTION

1.1 Climatic Background: Land-Sea: There is a demonstrated correlation between land-climate variations and sea surface temperature (SST) distributions in recent decades of good instrumental records. This has generally been characterized as the result of large scale interactions between the ocean and atmosphere, the most notable of which is the El Nino/Southern Oscillation (ENSO), known to produce teleconnections to land climate anomalies around the globe (e.g., Ropelewski and Halpert, 1987). Other work has demonstrated the even greater importance of tropical Atlantic SST variability for certain regions of the western hemisphere tropics, notably NE Brazil (e.g., Moura and Shukla, 1981; Hastenrath, 1984) and NW Africa/Sahel (e.g., Folland, et al., 1986). Larger-scale associations with climate also occur in the Caribbean and surrounding land regions of North, Central, and South America (Enfield, 1996). For example, changes in the precipitation patterns in the agriculturally sensitive Northwest Africa region appear to be associated with SST anomalies (SSTA) of the Gulf of Guinea (Figure 4 in Lamb and Peppler, 1991). During dry years, SSTA in the Gulf of Guinea is positive (warmer than mean values). Similar aridity associates with negative SSTA (cold anomalies) in the tropical North Atlantic, west of the Sahel, while either SSTA condition will typically result in greater-than-normal rainfall in NE Brazil. If the sense of
SSTA is reversed (cold Gulf of Guinea or warm North Atlantic), the climatic effects will also turn the opposite way (more rain in NW Africa and less in NE Brazil).

At interannual to decadal frequencies, the tropical North Atlantic (NATL) and South Atlantic (SATL) regions, and the tropical dipole that sometimes exists between them, have climate effects primarily in northwest Africa, northern South America, the Caribbean, and Central America. Enfield and Mestas (1999) and Mestas and Enfield (1999) have recently analyzed the global modes of SST variability in the residual global SST data (1856-1991) after first removing the global canonical ENSO variability (which confuses the role of non-ENSO modes). The residual modes are dominated by decadal-to-multidecadal time scales and include two mutually independent North Atlantic and South Atlantic modes (Figure 1). The NATL region (red tones in Figure 2, lower) forms part of a larger North Atlantic complex that extends all the way northward to Greenland with alternating nodes and antinodes of variability (Figure 3, left) and the NATL average is well correlated with the large scale North Atlantic mode series. Both are oceanic counterparts to the atmospherically defined North Atlantic oscillation (NAO; Hurrell, 1995). The SATL region (Figure 2, top) is unrelated to the North Atlantic mode but is highly coherent with a second rotated EOF mode from Mestas and Enfield (1999), seen in Figure 1 (right).

Rainfall: Because the NATL region is related to the larger scale NAO phenomenon, it is also related to the known climate linkages between the NAO and rainfall over the Mediterranean Sea, Central and northern Europe, and northeastern North America (e.g., Hurrell, 1995). However, the low-latitude rainfall effects are associated with NATL and SATL in a more direct way involving regional atmosphere-ocean interactions. Thus, the rainfall in NW Africa and NE Brazil is more directly related to anomalous meridional movements of the Intertropical Convergence Zone (ITCZ) toward one region (and away from the other), which are in turn related to meridional wind departures and anomalies in the meridional gradients of sea level pressure and SST in the ITCZ region (e.g., Wagner, 1996). All of these are associated with the SST anomalies farther poleward, in the index areas (SATL and NATL) shown in Fig. 2. By the
same token, the Atlantic SST is most highly correlated with rainfall in these regions when the SST anomalies on either side of the ITCZ oppose each other in the manner of a meridional dipole, or seesaw (Moura and Shukla, 1981). Dipole effects are statistically less noticeable at interannual timescales (Enfield and Mayer, 1997) and become more so at decadal periodicities, typically 10-20 years (Mehta and Delworth, 1995; Enfield and Mayer, 1997; Enfield et al., 1999).

Further climate linkages result from the interaction between SSTs in the eastern tropical Pacific and those in the tropical North Atlantic (NATL). It has been found that the tropospheric structures that favor rainfall over Central America, the Caribbean and northern South America are associated with a warm tropical North Atlantic and also with a cool eastern Pacific, while the opposite sense of this zonal seesaw enhances dryness over the same regions (Enfield and Alfaro, 1999; Giannini et al., 2000). Whereas a strong El Niño event in the Pacific will favor dryness, this climate effect would be more or less predictable depending on whether the tropical North Atlantic is cool or warm, respectively. During the out years between strong El Niño events the effect of the Atlantic on this region may account for most of the potential rainfall predictability.

**Tropical storms**: Rainfall anomalies are not the only effects associated with SST fluctuations. In the northern portion of the dipole region, off NW Africa, the summertime absolute magnitudes of SST vary within a narrow range. Here, departures of SSTs from normal (in excess of 27°C) may constitute one of the factors in determining the frequency and intensity with which tropical depressions born off NW Africa become tropical storms and hurricanes (Gray, 1990). During the several decades preceding 1970 Atlantic hurricanes were relatively frequent, then became infrequent after 1970. Around 1995, both the NAO and the North Atlantic rotated mode (Figure 1, left) switched sign again and hurricanes once again became frequent (Landsea et al., 1999). Two physical mechanisms are thought to underlie this relationship: both SST increases as well as their associated reduced tropospheric shear enhance hurricane development (Knaff, 1998).

**Time scale differences**: As the time scale increases from interannual to multidecadal, the spatially coherent SST variability expands poleward to include regions as far afield as Greenland, while the interaction with the atmosphere -- as evidenced by correlation with the pressure index for the North Atlantic Oscillation (NAO) -- also increases. These relationships appear to be related to prolonged, alternating cycles of warm/cool, dry/wet winters in Europe and eastern North America (Hurrell, 1995). Figure 1 shows the most important large-scale modes of Atlantic SST variability identified by Mestas and Enfield (1999). These rotated multivariate modes of global SST anomaly show that the tropical South Atlantic primarily is involved in decadal variability, while the North Atlantic works preferentially at a longer, multidecadal time scale. Unlike the interannual frequencies (Figure 2) where SATL extends into the Gulf of Guinea and includes the Sao Tome / Principe archipelago, at multidecadal time scales all of our proxy sites fall within the geographic domain of the northern mode, which extends farther south than NATL. It is clear that, to make sense of these differing time scales it is essential to have proxies from as many key sites as possible. In this proposal we advocate research to develop coral indices for both the Gulf of Guinea and the Cape Verde islands, both at locations that explain from 60% to more than 80% of the large scale variability represented by the NATL and SATL averages (Figure 2), as well as the North and South Atlantic climate modes (Figure 1).
1.2 Summary Of Work To Be Completed: We propose to reconstruct the past temporal variability and patterns of large scale tropical Atlantic SST, using long-lived Atlantic corals. This will be instrumental to better understand West African climate variability by exploring the statistical relationships between SST pattern variabilities, ITCZ, land climate, and corals. In particular, we wish to see how well the coral proxy indices replicate the relationships seen in the more conventional SST data sets. We can then use those relationships together with the longer coral records to infer the west African climate (from rainfall data archives and Gulf of Guinea runoff) much farther back in time and to answer some key questions regarding the secular variation of that variability. Successful extraction of longer proxy records will enable us (and others) to further explore: (1) the variations of tropical Atlantic SST statistics (including the demonstrated association of SST with short term climate variations in NW Africa and NE Brazil), the tendency for SST north and south of the equator to behave antisymmetrically (dipole), and the effects of these variations in SST behavior on land climate (especially rainfall...
over NW Africa); and (2) provide more temporal degrees of freedom for multidecadal SST variations by extending coral proxies farther back in time than our inadequate instrumental records reach.

2.0 STATEMENT OF WORK

2.1 Identification Of The Problem: There is a clear need for long-term climate data which surpasses the historical records of man. A primary source is proxy data, extracted from the remains of past biological or geological processes. “The origin of decadal to centennial-scale climate fluctuations is a major climate problem, for such oscillations hamper detection of a greenhouse signal. ... Thus, proxy climate records of the last 1,000 years represent an invaluable source of information” (Crowley and Kim, 1993). “Because of this need to understand long time scale climate variability ..., the further acquisition and compilation of pre-instrumental temperature data is thought to be of fundamental importance” (Kheshgi and White, 1993). Rind and Overpeck (1993) go on to say “The observed paleoclimate record contains many examples of apparently significant decade-to-century-scale climate variability. ... Because of insufficient global data, the worldwide synchronicity of ... temperature trends and their geographic distribution is in many cases not clear..., especially true for the earlier time periods when few instrumental records are available for low latitudes or the southern hemisphere. ... An important goal of climate research is to derive time series of climate forcing over recent geological history.”

2.2 Focus and Scientific Objectives: This proposal will capitalize on two related features for reconstructing climate: 1) demonstrated associations between Atlantic SST patterns and land climate, and 2) the existence of long-lived corals in key locations with good potential for reconstructing the temporal variability of those patterns. We seek to develop paleoclimatic records from the skeletons of annually banded corals growing in two regions of the eastern Atlantic: the Cape Verde Islands off NW Africa/Sahel and the equatorial Gulf of Guinea west of Lagos (Fig. 3). The Gulf of Guinea is embedded within a characteristic interannual variability pattern of SSTA in the equatorial and tropical South Atlantic (SATL) (Fig. 2 upper; see discussion in section 2.2.1). The SSTA's of the Cape Verde Islands are similarly embedded in the characteristic pattern for the tropical North Atlantic (NATL) (Fig. 2 lower). The coral-inferred SSTA's of both Cape Verde and Gulf of Guinea should be reflective of both the large scale NATL and SATL indices of SSTA, as well as their correlated land climate associations.

Our eventual aim is to reconstruct ocean climate history from these Atlantic corals over periods of 100’s of years, emphasizing the time before historical climate records. We expect to develop statistical relations between the present SSTA variability and the contemporaneous skeletal records from corals of the Gulf of Guinea and Cape Verde using stable isotope, Sr and Mg concentrations, and coral skeletal growth parameters. With such information, we hope to extend the temporal coverage of SST patterns allowing assessment of how they have been related to long term variations in precipitation, especially in NE Brazil and NW Africa.
2.2.1 Rationale for Examining African & Atlantic Climate and Corals: Our rationale for examining Atlantic corals is that they can help us reconstruct much of the tropical Atlantic SSTA, which we will take as synonymous with tropical Atlantic ocean climate, over time scales longer than those covered by the instrumental record. Prior studies of Pacific corals have similar rationale: they help to understand the ENSO-dominated ocean climate on time scales that transcend the instrumental record. It certainly appears that the statistics of ENSO-related climate variability (e.g., El Nino event intervals) are nonstationary on scales of decades to centuries (e.g., Enfield and Cid, 1991). Hence analyses based on a few decades of instrumental observations in the twentieth century can be misleading. The potential contributions of corals are great for understanding the longer-term variability of climate relationships. The same is likely true for the Atlantic SSTA. The NATL and SATL averages (or their coral proxies) are direct predictors for the land climates of NW Africa and NE South America. Coral proxies (of NATL) from the Cape Verde Islands offer further predictability for Central America, the Caribbean and northern South America (Enfield and Alfaro, 1999; Giannini et al., 2000), especially when combined with the counterpart proxies of other investigators from corals in the eastern Pacific.

One of the best hopes for predicting land climate over Africa and the Americas is to run coupled ocean-atmosphere numerical models (Barnston et al., 1994) to produce SST forecasts from one to several seasons into the future. The SST forecasts can then be used as input to covariant relationships between SST and other variables (rainfall, air temperature, wind) to produce climate outlooks for regions where such relationships are sensitive. Because the impacts of Atlantic SST are comparable to those of the Pacific, these methods must now be extended to the Atlantic ocean-atmosphere system. We know that the Atlantic system has significant decadal and multidecadal components (e.g., Fig. 1) as well as interannual, and that all must be understood. We also suspect that interannual relationships may undergo secular and interdecadal modifications, just as the production of Atlantic hurricanes seems to (Landsea et al., 1992), and as ENSO does in the Pacific (e.g., Enfield and Cid, 1991). It therefore becomes imperative to extend our analyses to longer time scales for which traditional, instrumental records are geographically inadequate and may contain artificial variations.

2.2.2 NATL and SATL proxies: The climatic argument for this proposal is that coral records for which the effects of SST and salinity have been properly separated can be used to extend Atlantic Ocean climate (SSTA) indices farther back in time than is feasible from instrumental records alone. The fortuitous location of Atlantic coral sites within the SSTA patterns (Fig. 2, 3), and near or on frequently traveled ship tracks, provides us with a unique opportunity to develop

Figure 4 Upper panel: Climatological mean salinity distribution in the eastern equatorial Atlantic, for the month of September. White contours are shown for even values (o/oo) and the islands of Sao Tome and Principe are shown as black asterisks. Lower panel: As in upper but for the month of December.
coral chronologies as SST pattern proxies over a much longer time span. From Fig. 2 we can see that both the Cape Verde Islands and the Sao Tome-Principe Islands lie near the $R = 0.8$ contours of correlation for local SSTA vs. The NATL and SATL indices, respectively, which are significant for climate variations over large land areas of the western hemisphere (Enfield, 1996). We can also see that these two locations are not redundant with respect to each other, i.e., each is correlated with one of the SSTA indices, but not with the other.

To the extent that the extracted local salinity relationships are related to nearby land climate (through local rainfall or continental runoff), they may also be useful as indices of regional climate behavior. In the Gulf of Guinea, salinity (Fig. 4,5) most likely reflects a complex combination of runoff from the Niger River (which drains a large basin north of the Guinea coast), the larger Zaire River (south of the equator), and seasonal upwelling that originates along the equator and propagates along the Guinea coast. (For upwelling influence, the trace element Ba may be particularly useful – see explanation in section 2.3). Once the SSTA and salinity components of the coral chronologies have been separated, we will have the means to verify the extent to which such relationships hold.

2.2.3 Gulf of Guinea: In the Gulf of Guinea, seasonal salinity and temperature variations are dominated by upwelling. This boreal summertime event (June-October) brings colder and more saline waters to the surface, replacing the usually warmer and fresher ones that are present the rest of the year (Bakun, 1978; Moore, et al., 1978; Philander, 1979; Picaut and Verstraete, 1979) (Fig. 5). "This occurs when a strong upwelling signal, generated by increased westward wind stress in the western Atlantic, can travel to the eastern Atlantic as an equatorially trapped Kelvin Wave (Moore, et al., 1978)." This event is believed to be unrelated to local coastal winds (Houghton, 1976; Bakun, 1978). Also influencing the Gulf of Guinea are the Niger river whose basin drains most of the southern part of the Sahara, and the Zaire river draining a large portion of Central Equatorial Africa (Fig. 4). Inspection of Levitus sea surface salinity (SSS) contours (monthly
averages for 1° by 1° grid) for that area indicates that peak fresh water discharge of the Niger river (Sept.) is noticeable and not drowned out by the much larger Zaire river whose mean annual discharge is approximately six times greater.

2.2.4 Cape Verde: Cape Verde is located well away from the influence of major rivers. Here changes in the surface salinity are probably only locally influenced by evaporation and precipitation (Fig. 6). Based on the change in salinity shown in Figure 6, the influence on the oxygen isotopic composition of the coral will be very small. We feel that the Cape Verde corals offer even greater potential as climate proxies (than SATL and the Gulf of Guinea) because: (1) they are uncomplicated by salinity effects; (2) the Cape Verde locations explains more than 80% of the large scale NATL SST index; and (3) the NATL index (as opposed to SATL) is a predictor for a more extensive region that extends westward across northern South America and the Caribbean to Central America.

2.4 Climate Proxies
2.4.1 Coral Growth Chronologies: Past work has demonstrated that coral growth, similar to that of tree growth or dendrochronology, can be environmentally and climatically sensitive. For example, Dodge and Lang (1983) found significant relations of high latitude coral extension rate with Mississippi river discharge. Dodge (1978) and Patzold (1992) have shown significant long-term relations of Bermuda coral growth with sea surface temperature over hundreds of years. Extension rate is only one parameter of coral growth. Density and mass information are also important to consider (e.g., Dodge and Brass, 1984). Lough et al. (1996) indicate “massive corals have enormous potential to provide well-dated information about a range of environmental variables for shallow-water tropical ocean regions... for up to the past 800-900 years...”

We have analyzed the extension, calcification, and density skeletal growth of several corals from the Gulf of Guinea. Visually evident on specimens from Principe is a pattern of density changes on an approximately decadal frequency. Fig. 7 is an X-radiograph positive showing banding and banding patterns of the corals. The average correlation of annual density among three Principe corals was $r=0.6$ (significant at $p<0.05$) for the 45 year period 1990-1946. This

Figure 7. X-radiograph positive print of *Siderastrea sp.* from Principe showing well defined density banding. (Scale: Length of coral is 21 cm.) Dates have been assigned from the known time of collections. Inset shows density master chronology of three corals from Principe. A marked decadal periodicity is evident.
correlation demonstrates similarity of growth among specimens and is consequently indicative of a common forcing function of the environment, which affects all corals. Averaging the three chronologies (Fig. 8 inset) filters random noise and enhances the common variation. A decadal rhythm is evident in the data. Our preliminary work suggests promise for extracting climatic and environmental data from coral growth parameters. The pronounced decadal frequency in the density chronology is suggestive of the long-term dipole.

2.4.2 Oxygen and Carbon Isotopes: The use of the carbon and oxygen stable isotope composition of the skeleton together with sclerochronology is an invaluable tool for reconstructing paleotemperatures over the 10 to 100 year time scale (Dunbar and Cole, 1993). This approach has been particularly successful in the Pacific where numerous workers are currently engaged in unraveling the ENSO signal (Cole and Fairbanks, 1990; Cole et al., 1992; and many others). In the Atlantic most of the research on isotopic records of corals has concentrated on the Caribbean. Many of these studies have not as yet addressed problems of regional climatic significance, being mainly concerned with local issues such as local sea surface temperature (SST) and precipitation. The work proposed here for the Gulf of Guinea, and Cape Verde.

Gulf of Guinea: Several corals were collected from the waters around Sao Tome and Principe in the summer of 1993. We shall discuss data from one of these (Swart et al.1998), collected from the north coast of Principe in waters 4 to 6 m deep. This coral has a record extending back 65 years to 1928 (Fig. 7,8). Originally we proposed that there should be a positive correlation between the δ¹⁸O of the corals skeletons and Sahel drought as during the drought years the Gulf of Guinea is 1 to 2°C warmer than normal (Lamb and Peppler, 1991). However, between 1928 and 1993 there is a negative correlation between the δ¹⁸O of the coral skeleton and the NATL (r= -0.41), but no statistically significant correlation between either SATL (r=0.30) or local COADS SST. The absence of a significant correlation between SATL and δ¹⁸O anomalies suggests that the δ¹⁸O signal in the Gulf of Guinea corals is not principally related to SST in this area. Furthermore, the absence of such a correlation cannot result from variations in local island precipitation as the highest precipitation occurs during warmer years and should actually enhance the normal inverse correlation between δ¹⁸O.

Figure 8 Relationship between Sahel precipitation (A), fluorescence (B), density (C) and oxygen isotopic composition (D) in coral from Principe. Note the positive shift in the oxygen isotopic composition coincident with the onset of low precipitation in the Sahel. Increases in density and decreases in fluorescence coincide with the drought (From Swart et al., 1998).
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 and Zaire rivers (Fig. 4). Using the mean rainfall averaged over 5 x 5° degree squares in the Niger and Zaire basins (Bigot et al., 1995) as an indicator of the amount of discharge from the Niger and Zaire rivers, 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 over this portion of the African continent (Fig. 8). 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 in the coral skeleton is being overwhelmed during the wet Sahel years by an increase in river discharge. Hence periods of drought in the Sahel are associated with higher salinities in the Gulf of Guinea and heavier oxygen isotopic compositions in the coral skeleton. These values occur in spite of higher temperatures and increased local rainfall in the Gulf of Guinea during the drought years.

Although we do not have coral data from Pagalu (Fig. 3), the oxygen isotopic composition in Sao Tome indicates an inverse correlation with SST and a much more stable uniform oxygen isotopic composition. We are aware of a possible connection between upwelling and salinity changes. According to the prevalent theory there should be an increase in upwelling associated with positive values of the Atlantic dipole and hence a positive correlation between the dipole and δ¹⁸O in the coral skeletons. There is in fact an inverse correlation suggesting that upwelling is not important in controlling the δ¹⁸O of the coral skeleton.

2.4.3 Fluorescence: The fluorescence record of the Principe coral reveals that there have been periods of high freshwater input into the Gulf of Guinea waters. The fluorescence and the ¹⁸O values for the Principe coral mostly have an inverse relationship, except for a few years in the mid-1940's. Over the record, when the fluorescence values are high, the ¹⁸O values are lighter, and when the fluorescence values are low, the δ¹⁸O values are heavier. There is a positive correlation between the annual averages of fluorescence for the Principe coral and the Subsahara precipitation anomalies (r= 0.45). The three islands Principe, Sao Tome, and Pagalu represent a transect away from the Niger and present an ideal opportunity not only to investigate SST, but also to examine directly a long term record of Niger discharge.

2.4.4 Sr/Ca and Mg/Ca Thermometry: The Sr/Ca and Mg/Ca ratios in coral skeletons have been shown to be dependent on the temperature and the respective ratios in the ambient water (Chave, 1954; Smith, et al., 1979; Mitsuguchi et al., 1996). High precision measurement of the Sr/Ca ratio in coralline aragonite by thermal ionization mass spectrometry (TIMS) suggests that it may be possible to determine monthly mean SST with the apparent accuracy of better than 0.5°C (Beck, et al., 1992). Although, the temperature dependence of Mg was shown in the early 1950s, its utility was largely discounted until recent work which has shown that it can reproducibly indicate the temperature of coral growth (Mitsuguchi et al., 1996). In our laboratory and in conjunction with Dr. H. Elderfield at the University of Cambridge in the United Kingdom we have investigated the Sr/Ca ratios in _Montastraea annularis_ as a function of temperature. A manuscript on this subject is the advanced stages of completion. As a result of the absence of funding for this project we have not started the critical study of changes in the Sr/Ca ratio of the skeleton from these corals which will reveal the extent of temperature changes in the Gulf of Guinea and enable an accurate extension back in time of the SATL index. This work will be the subject of this proposal.

2.4.5 Ba/Ca skeletal composition: It is well known that Cd and Ba in dated coral skeletal samples reflect former nutrient conditions, especially in regions marked by strong upwelling events such as the Galapagos (Shen and Sanford, 1990; Lea et al., 1989) or the coast of southern Oman (Tudhope et al., 1996). Furthermore, Ba is considered a chemical tracer of riverine input to the oceans (Shen and Sanford, 1990; Edmond et al., 1978; Hanor and Chen,
1977). We have experience with Ba measurements in corals for environmental reconstruction (Anderegg et al., 1997).

**Coral Growth Chronologies:** Past work has demonstrated that coral growth, similar to that of tree growth or dendrochronology, can be environmentally and climatically sensitive. For example, Dodge and Lang (1983) found a significant relationship between the extension rate of high latitude corals and the discharge of the Mississippi River. Dodge (1978) and Patzold (1992) have shown significant long-term relations of Bermuda coral growth with sea surface temperature over hundreds of years. Extension rate is only one parameter of coral growth. Density and mass information are also important to consider (e.g., Dodge and Brass, 1984). Lough et al. (1996) indicate “massive corals have enormous potential to provide well-dated information about a range of environmental variables for shallow-water tropical ocean regions... for up to the past 800-900 years...”

We have analyzed the extension, calcification, and density skeletal growth of several corals from the Gulf of Guinea and from the Cape Verde Islands. Figure 7 shows a coral from the Gulf of Guinea. Annual banding is present and is grouped in a decadal cycle. In the Gulf of Guinea we found the average correlation of annual density among three corals from Principe to be $r=0.6$ (significant at $p<0.05$) for the 45 year period 1990-1946. This correlation demonstrates similarity of growth among specimens and is consequently indicative of a common forcing function of the environment, which affects all corals. Averaging the three chronologies filtered random noise and enhanced the common variation. A decadal rhythm was evident in the data. The pronounced decadal frequency in the density chronology is suggestive of the long-term dipole.

Visually evident on specimens from Cape Verde were density changes, which was clearly annual density banding. Fig 7 is an X-radiograph positive showing banding and banding patterns of a specimen of Cape Verde *Siderastrea siderea*. Extension growth rate is very slow, on the order of 1 mm per year. Our preliminary work with densitometry of the bands suggests promise for extracting climatic and environmental data from Cape Verde coral growth parameters.

**2.4.6 Water Samples:** Although it is clearly not possible to instigate a detailed water monitoring program at both of these locations, we intend to deploy thermisters at the Cape Verde Islands and to have water samples returned to the U.S. for isotopic and salinity determinations. We already have made a contact in Principe who will deploy the thermisters and take water samples. We will arrange to have similar measurements made during or forth-coming trip to Cape Verde. Additional minor elements may be determined in these water samples (Sr, Mg, and Ca). Although these analyses will not enable us to make correlations to the material which we will sample, they will provide an indication of the variability in the salinity, isotopic composition, and temperature.

**2.5 Work and Study Plan**

The work, which we intend to carry out in this proposal, will be focused in two principal areas.

**A. Cape Verde:** For Cape Verde, we propose to return and to core and collect corals from a variety of islands. We visited Cape Verde in November 1999 and confirmed available literature reports (Laborel, 1974 and Wells, 1988) that sites for sampling are available and that very large slab colonies of *Siderastrea sp.* are present in shallow water, particularly in Sal and Sao Vincente. Coring of large flattened slab like specimens (up to several meters in size) is the most practical way to sample this species of coral and to achieve a long growth record. On these and other islands (e.g., Boa Vista) we also found sizable head-coral type specimens of *Porites astreoides* up to 70 years in age (extension growth rate of approximately 3 mm/year). Often equally large, but dead, specimens were also present. The dead specimens were only slightly bioeroded. Hence, the dead intact colonies offer a way to extend the sclerochronological record back farther than the 70 years offered by currently living corals. Our preliminary mission in
Cape Verde documented the presence of large corable and collectable corals. Preliminary analysis demonstrates the utility for further sampling.

**B. Gulf of Guinea.**

**Reanalysis of existing corals.** During the summer of 1994 we visited the islands of Sao Tome and Principe, funded by a small exploratory grant ($25K) from Climate Dynamics. This grant not only funded travel by four persons to the islands, but also supported a M.S. student. All analytical work was carried out at no cost to the project. As a result, we have been able to show (Swart et al., 1998), that there is a connection between precipitation in the Sahel region and changes in the oxygen isotopic composition of corals in the Gulf of Guinea. However, we need to replicate this work on additional corals collected during our visit and perform analyses on the Sr/Ca ratio of these corals so that we can independently examine the influence of salinity and temperature. The replication of our earlier results will hopefully confirm our original findings and demonstrate the robust nature of the stable isotope proxy in coral skeletons. We anticipate that approximately four additional corals will be analyzed (two each from Sao Tome and Principe) for oxygen and carbon isotopes, and two corals (one from each location) for Sr/Ca and Mg/Ca ratios. We will also conduct Ba/Ca analyses to investigate the utility of this upwelling/riverine tracer.

**Collection of new corals.** Our initial visit to the Gulf of Guinea was a reconnaissance made to assess whether corals even existed that could be used for paleoclimatic work. We found that clearly, not only do such corals exist, but we also observed larger and older corals, which will be able to extend the record of riverine runoff and temperature in the area. We have established a relationship with a local resort on one of the islands and will be able to gain information and use...
diving facilities during our next visit to collect longer cores. The three islands of Principe, Sao Tome, and Pagalu, form a transect stretching away from the influence of rivers and therefore we should be able to examine this influence in the oxygen isotopic composition. We propose to have access to a large vessel through a private donor. Using this vessel, once we have flown to Sao Tome, we will inspect reefs and collect coral samples from each of the three islands. We are especially interested in Pagalu. Available literature (Laborel, 1974 and Wells, 1988) suggests large corals are present. We will bring a coring rig and appropriate core barrels for sampling corals. Having logistics provided free by the donated vessel will facilitate operations.

2.5.2 Growth For extension and calcification growth as well as density determinations, X-ray negatives will be digitized as needed using a precision video camera and frame-capture board or scanner. Available software allows transects to be taken perpendicular to the density bands. Image optic density in the transect is converted into skeletal density by a computer program (Chalker et al., 1985; Dodge and Kohler, 1994). Growth parameters are divided into annual for the entire year and subannual (for the high density and low density band portions). A series of 17 annual and subannual growth parameters of each available year can be obtained using image analysis densitometry of coral X-radiographs. Fig. 9 shows a Cape Verde S. siderea X-radiograph and sample data obtained from a densitometry transect. Provided are the extension rate, average density, and calcification rate for all low and high density band portions as well as for each annual band (Dodge and Lang, 1983).

2.5.3 Stable Isotopes: The corals will be continuously sampled on a fine scale along a transect. Equipment constructed by Dr. Swart enables sampling to be carried out at resolutions as fine as 2 M. Samples will be analyzed using a Finnigan-Mat 251 mass spectrometer in the Stable Isotope Laboratory at RSMAS using as Fairbanks Device autosampler. Partial support for a replacement for this device is being requested from NSF in a separate proposal. It is anticipated that approximately 1,000 samples will be analyzed during each year of the project.

2.5.4 Sr/Ca and Mg/Ca Analyses: Minor and trace metal analyses: Mg/Ca, Sr/Ca, and Ba/Ca ratios will be analyzed by the Center for Isotopic and Trace Element Research at Old Dominion University. The lab is equipped with a Finnigan MAT Element2 high-resolution ICP-MS (a double-focusing, single collector sector field ICP-MS), and a Merchantek EO 266nm laser ablation system. Samples will be analyzed in solution-based and laser ablation modes, as both have advantages and disadvantages when applied to the analysis of coral skeletons. Coral powder isolated by microdrilling will be split between stable isotope and elemental analyses, to ensure exact alignment of the records. The powder will be dissolved in re-distilled nitric acid and then analyzed for the elements of interest. Two runs will be made for each sample – a run for high precision Sr/Ca ratios [precision of Sr/Ca ratios in otolith aragonite on our instrument is routinely 0.06% RSD following the method of Rosenthal et al. (1999) and Latkoczy and Thorrold (2000a)], and a second run to quantify the remaining trace elements of interest (Mg/Ca, Cd/Ca, Ba/Ca and Pb/Ca). Precision on the multi-element method is slightly inferior to the single element method (otolith aragonite, Mg/Ca = 0.67% RSD, and Ba/Ca = 0.5% RSD). We will also analyze several coral transects using laser ablation ICP-MS. Superior spatial resolution is obtainable with the laser ablation system (~ 20m), albeit at reduced precision. We have developed a multi-element laser method, similar to that outlined in Günther and Heinrich (1999), for analysis of coral and sclerosponge aragonite that has given the following precisions (%RSD): Mg/Ca = 0.98, Sr/Ca = 0.58, Ba/Ca = 0.84, Pb/Ca = 1.36, U/Ca = 0.76 (Latkoczy and Thorrold 2000b). The technique we will apply uses He to transport material from the laser cell to the mass spectrometer. This gas is mixed with Ar sample gas and a wet aerosol (introduced via a PFA micro-flow nebulizer) in a Scott double pass spray chamber. The nebulizer is, in turn, attached to an autosampler, and liquid standards are introduced throughout the sample run (every 5-10 samples) to monitor variations in mass bias.
2.5.5 Dating: Dating will be carried out using U-series methods by Dr. A. Eisenhauer at GEOMAR in Germany using standard TIMS methods.

2.6 Project Time Lines: We anticipate a three-year project. Funding is expected in August-September, 2000. During the first year we will utilize existing material from Gulf of Guinea and Cape Verde. Samples from multiple corals at both locations will be analyzed for stable O and C as well as trace and minor elements. We will mobilize and initiate drilling in the autumn at Cape Verde in the autumn of 2000. Upon retrieving samples and transportation to the laboratory, sequential studies will be conducted including X-radiography, oxygen and carbon isotopes, trace metal analyses, densitometry, and growth. We estimate that these samples will extend the range of growth records up to 200 years. At the same time we will collect dead heads from Cape Verde and these will be dated by Dr. Eisenhauer. These samples will be analyzed for the isotopic and trace element composition in the Spring of 2001. In the fall of 2001 we anticipate returning to Gulf of Guinea. We have only included funds for a trip to join a yacht of opportunity, which we anticipate, will be in the area during this time frame.

2.7 Expected Results: After collection, corals will be slabbed, X-radiographed, dated, and analyzed using sclerochronology, oxygen and carbon stable isotope analysis, and Sr/Ca - Mg/Ca thermometry. Sampling will be at approximately a bimonthly scale, to obtain good resolution for annual climate parameters. Results of these analyses will be compared to historical climate variable time series. Statistical relations between these results and the historical time series will be obtained and used to extend the historical climate record. Results of our proposed research will provide several fold benefits to the public and scientific community. These include an extension of the historical climate records of the West African Subsahara and of the Central African Gulf of Guinea. Additional and long-term climate series will be useful data sets for testing output of current models and for developing new models to understand dynamics of this region. Because the frequency and occurrence of droughts of the Sahel Subsahara appear related to frequency and occurrence of hurricanes impinging on the east coast of the United States and drought in north-east Brazil, the public and scientific community may benefit greatly through enhanced understanding and eventually hurricane prediction.

2.8 Project Management: This project will be headed by Dr. Peter Swart, Dr. Richard Dodge, Dr. Simon Thorrold, Dr. A. Eisenhauer, and Dr. Enfield. Dr. Dodge will be in charge of specimen X-radiography and densitometry. Dr. Swart will be in charge of isotopic analyses. The chemical analyses will be performed in the laboratories of Dr. Thorrold. Dr. Eisenhauer will be responsible for dating aspects of the project. Dr. Mestas will participate in data and climate analyses with special emphasis on statistical relations involving climate data sets (SST, rainfall and runoff). Dr. Enfield, who has collaborated extensively with Dr. Mestas on large scale climate variability, will act as a consulting collaborator on physical issues and climate analysis strategies, and also as our link to the wider climate community. Drs. Enfield and Mestas are currently supported under a NOAA (Office of Global Programs) PACS project to study the effects of the Atlantic and Pacific on Intra-American climate variability. Our work will build on that effort and extend it to the west African sector. The climate analysis will further benefit from critical work being done at AOML on hurricane frequency relationships (Landsea and Goldenberg at AOML, coordinated through D. Enfield.