C. PROPOSAL NARRATIVE

Results from Previous NSF Support

**Swart**

1- OCE-9819147 and 0136941: A Multi-tracer calibration study of sclerosponges

Sclerosponges have been stained with Calcein and grown for three years in the field. Currently these samples are being analyzed in order to establish correlations between geochemical parameters such as oxygen and Sr/Ca and temperature. Full citations for these publications are included in the reference section of this proposal.

**Abstracts**

Rosenheim, B E, Swart, P K, Thorrold, S., Rubenstone, J., 2001., AGU abstracts

**Papers**


**Swart /Mestas-Nuñez/Dodge**

2- OCE- 0081770 : Inter-annual to Century-scale Climate Records from the Atlantic

This proposal started in October 2000. Field activities occurred in March 2001 and June 2002. A Ph.D. student, Chris Moses(UM) has started re-analyzing and sampling material in hand. A student at NOVA, Kevin Helmle is using some of the material for his thesis. Full citations for these publications are included in the reference section of this proposal.

**Abstracts**

Moses, C., Swart, P.K. Dodge, R.E., Helme, K., Thorrold, S., 2002., AGU
Swart, P.K., A Saied, C Schroeder, L Williams, 2003, AGU Abstract

**Terrence M. Quinn**

3- OCE-0221750; $270,711; 8/02–7/04: A Coral Perspective on Holocene Climate Variability in the Tropical Western Atlantic

Thirteen fossil Montastraea annularis coral heads, which range in age from 1.61 ka to 9.63 ka, have been collected from the Dry Tortugas, Florida. These coral heads are pristine, based on preservation of
modern marine initial $\delta^{234}$U ratios, X-ray diffraction and petrography. Stable isotopic (oxygen and carbon) and Sr/Ca ratio determinations will be made on each of these fossil coral samples. Geochemical time series of multidecadal length from two mid-Holocene corals (4158±21, 4514±46) indicate ~1°C warmer than modern conditions, which is consistent with increased solar insolation at this time w/r to modern. Stable isotope and Sr/Ca data document the presence of a strong annual cycle in these coral samples. A reliability study, using 3 modern *M. annularis* heads from the Keys, indicates mean SST can be reconstructed to within ±0.3°C. Research performed with funding from this grant will constitute the Ph.D. dissertation of Jennifer Smith.

**Publications**

Data acquisition in progress. Presentation scheduled at Fall AGU 2003.

**Data description**

Data will be archived at World Data Center in Boulder, CO.

**Amy Clement**

4- ATM-0134742: CAREER: The Earth’s Climate. Understanding the Past and Educating for the Future. Research has been carried out on the effect of precessional forcing on the tropical climate. We have found that by reconsidering the role of precessional forcing in the tropics, a different picture of past climate change emerges. In particular, our results emphasize the differences between thermodynamic changes (as expressed in temperature related fields) and hydrologic changes.

**Papers**


**Introduction**

This proposal outlines a collaboration between The University of Miami (Swart, Mestas-Nuñez, and Clement), Nova Southeastern University (Dodge), the University of South Florida (Quinn), Winter (University of Puerto Rico), and NOAA-AOML (Dr. D. Enfield). In order to study the interaction between salinity, water temperature and climate in the Atlantic, we have collected a suite of corals (*Montastraea faveolata* and *Siderastrea siderea*) from the Greater and Lesser Antilles (Windward and Leeward Islands) in the Caribbean (Figure 1). These island include St. Thomas, St. Croix, St. Martin, Barbuda, Antigua, St. Kitts, Montserrat, Guadeloupe, Dominica, Martinique, St. Lucia, and St. Vincent and the Grenadines. In addition we propose to use corals already collected from Puerto Rico as well as corals to be collected from the Bahamas. The location and preliminary X-radiographs are

---

**Samples 2002 Cruise**

*Figure 1: Sites of core collection and water samples. Also shown are the location of the cores for which preliminary data are presented in this proposal, St. Croix, Guadeloupe, and Union Island. Samples from Union Island, Guadeloupe, and La Paguera will be analyzed for this proposal. An additional coral will be cored in 2004 from the Bahamas.*
visible at the following web site (http://www.nova.edu/ocean/ncri/case/cores/index.html). We suggest that the geochemical analyses of coral skeletons from this area act, in essence, like a strip chart recorder, recording variations in salinity and temperature relating to different water masses penetrating into the Caribbean through the Lesser Antilles. In total over 35 cores, typically between 150 and 200 years in age were collected. In addition we have a core from Puerto Rico which represents in excess of 300 years of coral growth. Together with our existing core collection from Florida we have corals which stretch over almost 15° of latitude, a spread unprecedented in the Atlantic Ocean. This collection effort was completed with support from the National Coral Reef Institute (NCRI), the National Center for Caribbean Coral Reef Research (NCORE), the Florida Institute of Oceanography (FIO), and the Stable Isotope Laboratory at RSMAS (SIL). This proposal outlines rationale and requests support for the analysis of the density banding, minor elements, and stable isotopes in these samples as well as the collection of additional cores from the Bahamas and the Turks and Caicos. In particular our results will test the following hypotheses:

**Hypothesis 1:** Salinity in the Caribbean varies on an inter-annual time scale which can be linked to climate induced temperature oscillations in the northern (TNA) and southern sub-tropical Atlantic (TSA).

  **Sub-hypothesis 1a:** Salinity in the sub-tropical Atlantic gyre responds to wind forcing which in turn is related is positively correlated with temperature anomalies in the southern sub-topical Atlantic.

  **Sub-hypothesis 2a:** Salinity differences between the northern and southern portions of the Lesser Antilles relate to variations in the relative difference in temperature between the TNA and TSA as well as the position of the ITCZ and the input from the Amazon and Orinoco.

**Hypothesis 2:** Long term changes in the salinity and temperature of the Atlantic can be documented utilizing proxy geochemical and density information in coral skeletons.

  **Sub-hypothesis 2a:** Increases in salinity of the Atlantic ocean can be documented using Sr/Ca and oxygen isotopes at sites in the Bahamas.

**Hypothesis 3:** Salinity information obtained from the coral reconstruction can be utilized to validate oceans models such as the Hybrid Coordinate Ocean Model (HYCOM)

**Background**

**Coral Skeletons as Climatic Indicators**

**Proxy Geochemical Indicators:** Proxy geochemical indicators in coral skeletons can reveal information regarding the salinity and the temperature of the environment in which they form, the $\delta^{18}$O being influenced by salinity and temperature (Weber and Woodhead, 1972; Fairbanks and Dodge, 1979; Swart and Coleman, 1980), while the Sr/Ca ratio is influenced primarily by temperature only (Weber, 1973; Beck et al., 1992). The principals behind $\delta^{18}$O and Sr/Ca are well established and have been discussed in numerous papers and therefore will not be elaborated in this proposal. Other proxies such as $\delta^{13}$C, Ba/Ca, U/Ca, and Mg/Ca also indicate environmental variability although the interpretation of many of these is still controversial and in some instances equivocal. While there are still some uncertainties, most coral geochronists would agree that analysis of the $\delta^{18}$O and Sr/Ca ratio of coral skeletons in the context of the annual density bands or other chronological markers can reveal information regarding the salinity and the temperature of the ambient environment. Although there have been numerous papers which have presented extended time series in the Pacific (Cole et al., 1993; Quinn et al., 1998; Linsley et al., 2000; Cobb et al., 2001; and others), few long records obtained from coral skeletons exist in the Atlantic. However, results from the University of Miami group have calibrated $\delta^{18}$O and Sr/Ca with temperature in the coral species most commonly studied in the Atlantic, Montastraea annularis
These correlations have been confirmed by Wantabe et al. (2002) and unpublished data from UM and USF. One question which is repeatedly asked by those not familiar with the various analytical methods involved, is to what precision can the salinity and/or the temperature of the water be determined using proxy indicators in coral skeletons. Although the answer to this question principally depends upon the skill and the knowledge of the persons sampling the coral skeleton, under the best case scenario it is possible to reproduce the $\delta^{18}O$ of a coral skeleton to better than 0.07 ‰. This variation corresponds to either a change of 0.25°C or 0.25 physical salinity units (PSU), or some combination of salinity and temperature. The Sr/Ca ratio in a coral skeleton can be measured using ICP-OES to a precision of 0.3% (RSD). Hence a variation in the Sr/Ca ratio of 0.01 mmol/mol (equivalent to 0.3% RSD) would equate to about 0.25°C change in temperature. In summary using a combination of Sr/Ca and $\delta^{18}O$ it is therefore possible to calculate both salinity and temperature to a precision of 0.25°C for temperature and 0.25 PSU for salinity.

**Chronology And Coral Density:** The time scale for the geochemical data obtained from the coral can be obtained from two independent sources. First, many massive corals typically form annual dense bands during the summer months. By simply counting the bands, the age of the sample can be obtained. A second method is to use the annual cyclicity of parameters such as the $\delta^{18}O$ and the Sr/Ca ratio and then counting the cycles. Ideally these two methods should agree. However, in some instances it is possible that the coral will fail to leave a clear annual band in the skeleton. This occurs typically when the coral comes under severe stress as a result of either high or low temperatures or some other environmental perturbation. For example it has been shown that bleaching events can result in the coral missing a years growth (Leder et al., 1991). Similar to some trees under dendrochronological analysis, the skeletal growth records of reef-building corals can show significant correlation between colonies, within and between reefs, and with environmental factors. Even if between-colony correlation is not high, ensemble averages into master chronologies can provide a composite environmental signal (Dodge and Vainsnys 1975, Dodge and Lang 1983). Dodge and Helmle 2003 have recently demonstrated a strong level of correlation for extension rate within and between corals sampled throughout Southeast Florida reefs as well as within and between species, i.e., Diploria labyrinthiformis and Montastraea annularis. The strongest environmental correlate of these density data from Southeast Florida was with seawater density (sigma T), a combined effect of temperature and salinity. Because there were no significant correlations between annual average coral extension and temperature, it is reasoned that the correlation of coral extension with seawater density is attributable primarily to salinity. The degree of correlation of time series of coral growth parameters with historical temperature and salinity data will yield information about the dominant influence on skeletal accretion over the latitudinal range of coral cores (~15°), in binned ranges of 5°, as well as over the length of the growth records available, (50+ years). Further, we can use the isotopic records of salinity and temperature to test the relationships of growth over time.

**Temperature**

Empirical studies have already demonstrated the interrelationship of various regional climate systems to sea surface temperature (SST) variability in the Atlantic (Moura and Shukla, 1981; Folland et al., 1986). These include the rainfall in the northeastern region of Brazil (Hastenrath and Greischar, 1993) and northwest Africa (Folland et al., 1986). Variations in the interannual-to-decadal climate variability have been suggested to be dominated by a (1) dipole pattern in SST (Weare, 1977) between the northern and southern tropics, across the Intertropical Convergence Zone (ITCZ), (2) an El Nino-like variability (Enfield and Mayer, 1997). Enfield and Mayer (1997) and Enfield et al. (1999) have shown, through an analysis of temperature data, that the regions north and south of the ITCZ are statistically independent of each other, thus confirming the findings of Houghton and Tourre (1992). The TSA mode is located south of the ITCZ centered on the Gulf of Guinea southward though a region off the coast of Namibia.
is characterized by higher than normal temperatures in these regions coupled with intensified trade winds between 10° and 30°N. In contrast the TNA mode is dominant in the central and eastern Atlantic and extends all the way across the Atlantic to Central America during January, February and March of each year. This mode is associated with a reduction in the dominantly easterly trades in the northern hemisphere, in turn producing an increase in the surface heat flux into the oceans and a reduction in evaporation. The concurrence of SST anomalies with surface wind changes in the western equatorial Atlantic produces a positive feedback similar to that proposed for the Pacific ENSO (Bjerknes, 1964). 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 (TNA minus TSA) is itself an index of dipole intensity. It is well established that there has been an increase in the global temperature over the past 100 years. These increases are pronounced in the atmosphere, where an increase of approximately 1°C has been noted since the late 1800s, but rather less noticeable in the marine realm. This absence of increase is manifest in the TNA and TSA. Increases are barely visible in the TNA, while in the TSA the increase is approximately 0.5°C.

**Atlantic Temperature Variability and Tropical Western Hemisphere Warm Pool (WHWP):** The area of correlated temperature in the northern sub-tropical Atlantic (TNA) has a correlation of 0.5 with the WHWP (Wang and Enfield, 2001, 2003) which itself extends from the eastern North Pacific to the Gulf of Mexico and the Caribbean. The WHWP is defined as consisting of water warmer than 28.5°C.
and shows a large annual cycle with significant departures in areal extent and intensity. As the warm pool develops, warmer SSTs are associated with a warmer and wetter troposphere, a reduction the sea-level pressure, reduced easterly trades, less wind shear, and weaker upper level subsidence (Gray, 1968; Knaff, 1997). A strong, well developed WHWP is therefore conducive to a strong rainy season as well as a higher frequency and a greater intensity of tropical storms and hurricanes (Lansea, 1993; Enfield, 1996). Hence the TNA operates in two modes to control climate in the Atlantic. First in conjunction with the TSA, the TNA controls the position of the ITCZ in the Atlantic which in turn governs the flow of saline and less saline water through the Leeward and Windward Islands into the Caribbean. Second the TNA is correlated to WHWP whose spatial development controls the rainy season and influences the development of hurricanes in the Atlantic.

**North Atlantic Temperature Variation:** Sea-surface temperature (SST) variation in the North Atlantic is not correlated to either the TNA or TSA. Long term variability is described by the Atlantic Multi-Decadal Oscillation (AMO) (Kerr, 2000; Enfield et al., 2001). Temperature variation in the region is also related partially to the North Atlantic Oscillation (NAO), a pressure difference between the Azores and Iceland. The NAO is correlated to a so-called tripole of temperature variation, including a positive correlation with temperature off the eastern seaboard of the U.S. and a negative correlation with a region corresponding to the TNA region.

**Temperature Variability in the Caribbean:** Temperature variability in the Caribbean is strongly correlated to the TNA which in turn is related to the WHWP. This can be seen clearly in a 14 year time series (Fig. 4) from the three localities from which we present preliminary data in this proposal (St. Croix, Guadeloupe, and Union Island). All show almost identical temperatures with the exception of winter temperatures in Union Island which can in some years be 0.5 to 1°C warmer. Temperature from Puerto Rico is similar to temperatures at Guadeloupe and at St Croix. The mean annual temperatures for the same time period are also shown in Figure 4 and correlate well with the TNA.

**Salinity**
The surface salinity of waters within the Caribbean are influenced by circulation from two principal sources of water (Schmitz, 1996). The first source is recirculation of relatively saline water within the North Atlantic sub-tropical gyre. This water possesses relatively high salinity (36 to 38) (Worthington, 1976) (Fig. 3) as a result of enhanced evaporation in the subtropics and is driven into the northern Caribbean through the passages between the Greater Antilles and Windward Islands principally as a result of wind stress. Increases in recirculation driven by prevailing easterly wind direction increases the influence of the sub-tropical gyre on the Caribbean. The second source of water affecting the Caribbean is derived from the tropics driven by cross-equatorial advection of the upper limb of the Atlantic thermohaline cell. This water is less saline (34 to 36) than the sub-tropical gyre water (Worthington, 1976) being strongly influenced by precipitation related to the Intertropical convergence zone (ITCZ) and contributions from major rivers such as the Orinoco and the Amazon. From the north to the south of the Lesser Antilles unpublished data indicates a mean difference in salinity of 2 PSU.

The vertical distribution and movement of water in the Caribbean has been studied by various workers (Wust, 1964; Morrison and Nowlin, 1982; Wilson and Johns, 1997; Johns et al., 2002). Based on Sverdrup theory and numerical model results, the work of Wilson and Johns (1997) confirms the general premise of this proposal, that very little of the mean inflow into the Caribbean through the southern passages can be attributed to wind-driven circulation and most is derived from South Atlantic waters crossing the equator in the upper limb of the Atlantic thermohaline cell. Water derived from the sub-tropical Atlantic gyre and the upper limb of the thermohaline cell enters the Caribbean through the passages in the Leeward and Windward Islands (Fig. 1). The Greater Antilles including Puerto Rico, Hispaniola, and the U.S. Virgin Islands as well as the Lesser Antilles (incorporating the Leeward and
The Windward Islands (Windward Islands), are influenced by the saline water derived from the sub-tropical Atlantic Gyre (Fig. 3). The Windward Islands are dominated by the less saline water related to cross-equatorial advection. The lower salinity of this water results from the mixing of saline water, moving south from the sub-tropical gyre, with meteoric waters derived from precipitation and riverine runoff (Zhang et al., 2003). As these waters penetrate into the Caribbean they mix by the time water reaches the Yucatan Peninsula and move north into the Gulf of Mexico forming the Loop current and the Florida Current moving north to the region of North Atlantic Deep Water (NADW) production. The relative strength and variation of this flow and NADW production is a significant signature of climate variation. In contrast to ENSO, which is thought to be primarily a low-latitude basin spanning process, in the Atlantic variation in the so-called Global Conveyor Belt involves northward movement of near surface waters. This movement carries with it low-salinity water into the Caribbean. As changes in the equatorial heat transport have been proposed as a mechanism for explaining decadal-to-centennial climate variation seen in many instrumental and proxy records (Bond et al., 1993; Broecker, 1997), monitoring such transport using the Caribbean would provide valuable information on past changes in this flow.

Several models have been developed to explain temperature anomalies, wind-stress, and resultant ocean circulation patterns (New et al., 1995 and others) in the Atlantic. In the following section we discuss several models which might link salinity variations in the Caribbean to oscillations in the temperature regime in the Atlantic. In the model proposed by Chang et al. (1997), the warm temperature anomaly between 10 and 30°N would result in an increased northerly transport of colder water from the south, particularly the western boundary currents, such as the North and South Brazil currents. Horizontal advection of heat will therefore act against atmospheric warming in the north and cooling in the south. In addition, atmospheric radiative and turbulent energy fluxes would damp out SST anomalies providing negative feedback. As these feedbacks balance each other, a self sustained oscillation would be established. If this model of temperature feedback and oscillation is correct, then variations in the TSA and TNA modes would have significant impact on the source and nature of the water entering the Caribbean (Figure 1). First, during periods of increased TSA (warm temperatures in the Gulf of Guinea) temperature phenomenon, the easterly trades would be intensified causing an increase in the importance of the sub-tropical equatorial gyre and an increase in salinity in the north of the Lesser Antilles area. Increased north-to-south transport would have the effect of further reducing the influence of the cross-equatorial transport of relatively low-salinity water. In contrast, during periods of increase in TNA, the easterly trades would be reduced, causing a consequent reduction in the influence of the sub-tropical gyre on the salinity of the Caribbean. The northerly transport of colder and less saline
Figure 4: Temperature data from three locations representing corals which will be sampled in this proposal (data from IGOSS) together with instrumental data from La Paguera in Puerto Rico. Note the similarity in temperature between the locations. Summer temperatures are essentially the same, while winter temperatures are in some years up to 1°C cooler in St Croix. In other years however there appears to be no difference between the southern and northern end of the Lesser Antilles. The insert shows the same data treated with a 12 sample smooth (annual). Also plotted is the TNA for the same period. Differences between the locations are small (< 0.5°C).

Water from the equatorial region would act to reduce the temperature anomaly in the northern Atlantic. If this scenario is correct, increases in the TNA should correlate with decreases in salinity, particularly in the lower portion of the Lesser Antilles arc.

A second mechanism of linking salinity variations to TNA and TSA relates to the magnitude of the dipole and the position of the ITCZ. In our scheme, positive values of the dipole mean that the Cape Verde area is relatively warm and the Gulf of Guinea area relatively cool. Under this arrangement the position of the ITCZ would be in a northerly position leading to less precipitation over the equatorial region. Conversely, more negative values of the dipole would mean that the ITCZ is positioned to the south bringing higher amounts of precipitation to the equatorial regions of the Atlantic. Generally speaking, when the dipole has positive values there is higher rainfall over Africa, but lower precipitation in the Nordeste region of Brazil. Hence in this model, lower salinity in the Windward Island area should be associated with negative values of the dipole (positive correlation between the dipole and salinity).
It has also been suggested that the southern Caribbean can be influenced by the input of riverine waters from the Orinoco and Amazon (Muller-Karger, 1988) which itself is dictated by the extent of precipitation over South America ($r=+0.4$, $p>0.05$). Muller-Karger’s work has shown that water from the Amazon typically travels north along the NE coast of South America and is seasonally pushed into the Atlantic by a retroflection of the North Brazil Current (NBC). The seasonal retroreflection occurs between June and January each year when the ITCZ moves to its northerly position. When the ITCZ is in the south, the NBC weakens and the Amazon flows northeastswards towards the Caribbean combining with water derived from the Orinoco. Hence it could be argued that during years which are characterized by high dipole values, the Caribbean is less influenced by riverine discharge.

**Long Term Changes in Salinity of the Atlantic:** Changes in the salinity of the oceans have only recently been documented (Curry et al., submitted) based on actual physical measurements and been implied from proxy data in corals in the Pacific (Hendy et al., 2002;) and in sclerssponges (Rosenheim and Swart, unpublished data). Results from the Atlantic suggest that the salinities may have increased by between 0.1 and 0.4 over the past 40 years as a result of increased evaporation/precipitation (E/P) ratios. A combination of an increase in temperature (which acts to decrease the δ¹⁸O of the coral skeleton) together with an increase in the salinity of the magnitude discovered by Curry et al. (which acts to increase the δ¹⁸O of the coral skeleton) will act to mask the change in δ¹⁸O recorded in the skeleton.

**Salinity vs. Oxygen Isotopic Relationships:** A key parameter necessary in order to use the δ¹⁸O of the coral skeleton to assess the variation in salinity is the relationship between the salinity and the δ¹⁸O of the water. This relationship is known to vary globally in the oceans depending upon the source of the freshwater component. We have over the past several years been conducting analyzes using samples obtained from various 'ships of opportunity'. The first set of data is derived from a series of cruises in 1997 by Doug Wilson and Bill Johns. In addition we collected samples during our 2002 cruise. Since March 2003 we have collected samples on a fortnightly basis from stations throughout the northern Caribbean and the Bahamas. Finally, Amos Winter has had analyzed 12 months worth of samples collected from Puerto Rico. While the δ¹⁸O of all these samples from the various localities (Fig. 5) show slightly different intercepts, there is a remarkably constant slope between δ¹⁸O and salinity corresponding to about 0.2 ‰ for a change of 1
PSU. Hence if our reproducibility of the mass spectrometer is 0.1‰ then we could use the $\delta^{18}O$ of the coral skeleton to detect changes in salinity of 0.5 PSU.

**Existing Coral Records in the Caribbean**

In contrast to the Pacific, there have been relatively few published geochemical records from corals in the Atlantic. In fact an examination of the NOAA paleoclimate database reveals an absence of continuous modern coral records from anywhere in the Atlantic. There are however some data published from the

![Graph](image.png)

**Figure 6**: The $\delta^{18}O$ from three specimens of Montastraea faveolata (locations shown in Figure 1). The data have been subjected to a five sample smooth only. Data from Union Island are the same as shown in Figure 5. Temperature records are shown in Figure 4. Clearly there is little difference between St. Croix and Guadeloupe, the small offset between these two corals is typical of inter-specimen differences. The difference between these two and the coral from Union Island must be related to salinity as the temperatures are similar between these two localities except during the winter. The difference between the $\delta^{18}O$ records has been converted to a salinity difference using the data in Figure 5 (assuming a 0.2‰ difference for every 1 PSU change in salinity). The maximum salinity difference seems to occur during the winter. The Sr/Ca data will allow a correction to be made for differences in temperature. Without these data we estimate that the maximum salinity differences estimated in this preliminary data may be too high by 0.5 to 1 PSU. The above comparison is based on a chronology calculated assuming the density bands formed at the same time during each year in all three corals. We propose to refine the chronology using the Sr/Ca ratio, as we know that temperatures follow the same pattern at all three localities.

Florida Keys (Swart et al., 1996b) and the eastern Atlantic Swart et al. (1998) and there exist various unpublished datasets from our group covering areas in the Caribbean (Belize, Florida, Trinidad and Tobago, and Dominica) and the Dominican Republic (Greer, 2002) as well as Puerto Rico (Winter, et al.,

C- 10
In the Gulf of Guinea (Figure 4), positioned in the eastern Atlantic, we have shown a strong correlation between the oxygen isotopic composition of the corals and the rainfall in the Sahel region, while in the Cape Verde region (Figure 4) we have recently completed a 120 year record. The $\delta^{18}O$ of this record shows an inverse correlation with SST as might be expected. However, the magnitude of the correlation coefficient is only -0.5, suggesting that there are other controls, probably salinity, which are important in the area. The records from Puerto Rico offer perhaps the best probability for correlation with the TNA, as an examination of Figure 4 shows a high degree of correlation from the Caribbean to the north-east sub-tropical Atlantic, however as yet these records have only been partially analyzed. In order to provide a more complete dataset, we collected a suite of corals from the Lesser Antilles. The Leeward and Windward Islands are particularly well suited to studying long-term changes in temperature of the TNA and WHWP as well as salinity variations combined with the relative contributions from sub-tropical Atlantic Gyre and cross equatorial transport. The Lesser Antilles including from south to north the islands of Grenada, St. Vincent, St. Lucia, Martinique, Dominica, Guadeloupe, Antigua, Barbuda, St. Martin and the Virgin Islands are all surrounded by corals reefs which potentially sample, in the oxygen isotopic composition of their skeletons, the salinity of the waters which pass by the reefs. The critical islands of Guadeloupe and St. Lucia mark the region of potential separation between the two competing water masses. Corals from these locations can be expected to be very sensitive to variations in the contributions from these two sources. Islands further to the south and north may also be influenced depending upon the magnitude of changes in the contributions from the two sources. As mentioned earlier in this proposal we have material from most of these islands in hand. The mean SST for the Windward Island region is relatively constant (Figure 4) and time series data suggests that the entire region will exhibit similar inter annual variation in SST during the summer months. During the winter months the northern end of the transect will be up to 0.5 to 1°C cooler in some years. Hence inter annual variability in the $\delta^{18}O$ should be mainly a reflection of changes in salinity rather than temperature. Nevertheless the multi-proxy approach of using Sr/Ca as well $\delta^{18}O$ should enable changes to be resolved. In addition to collecting all these samples at no cost to this proposal we have analyzed five years of skeletal material for $\delta^{18}O$ (sampled at a resolution of 12 samples per year) from three of the specimens collected from the U.S. Virgin Islands, Guadeloupe, and Union Island (St Vincent). Based on temperature records obtained from IGOSS data (Figure 4), there should be little difference between these three localities and therefore the differences in the $\delta^{18}O$ of the skeleton between these localities should reflect differences in salinity. As may be observed from these data (Figure 6), the $\delta^{18}O$ of the coral skeletons show a progressive isotopic depletion from north to south, consistent with the interpretation expected and outlined in this proposal. In order to obtain a preliminary estimate of whether salinity can be ascertained using this approach we subtracted $\delta^{18}O$ values obtained from Guadeloupe and Union Island (St. Vincent), from St. Croix. We then converted these differences to salinity using the relationships shown in figure 5. These data are

Figure 7: Salinity output from the MICOM model showing the interaction of salinity along the Lesser Antilles. Data which will be generated in this project will help to test such models.
shown in Figure 6 and indicate an increasing salinity depletion towards the south of the Lesser Antilles. This difference is seasonal with the maximum difference being manifest during the winter, after with the peak discharge of the Amazon-Orinoco. The magnitude of the difference are consistent with the limited salinity data which exist for the area as well as estimates obtained using HYCOM.

**Linkages with the Hybrid Ocean Model (HYCOM)**

Many of the salinity features discussed in this proposal are well simulated in numerical simulations of the North Atlantic basin performed with the Miami Isopycnic Coordinate Ocean Model (MICOM) and its successor, the HYbrid Coordinate Ocean Model (HYCOM). An example of the model salinity field is shown in Figure 7 which clearly demonstrates the salinity differences along the Lesser Antilles. If funded, the ocean model will be used to evaluate the physical linkages between the large-scale climate mechanisms and the salinity signals in the corals. A first step will be to analyze existing runs with the model (Chassignet et al. 2003) to study the spatial and temporal variability in the salinity field of the Caribbean. A preliminary example of what could be done is shown in figure8. In this example the difference in salinity between the northern and southern end of the Lesser Antilles has been estimated from the model. Although we do not have data from the corals which covers the same time period, it can be clearly seen that there is interannual variability which has been replicated by the coral data. Further experiments may be performed in order to isolate the effects of surface forcing associated with particular climate phenomena (e.g. the TNA, the TSA, ENSO) on the salinity field.’ No direct funding is requested for this component although students involved in this project may attempt some preliminary simulations in preparation for later more involved studies.

**Work Plan**

◆ **Isotopic Analyzes:** We propose to analyze 3 corals (Puerto Rico, Guadeloupe, and The Grenadines). We consider that these are the most critical areas for examining variation in salinity and therefore we will analyze these at an intra-annual resolution. During the second year we will start on the coral which we will collected from the Bahamas. All of these four corals will be analyzed at a resolution of 10 to 12 samples a year in order to capture seasonality. This is the same resolution which we analyzed the corals shown in Figure 7 and appears to be sufficient to reveal the seasonal amplitude. This will require approximately 1500 analyzes per coral (assuming a record of 150 years). The coral from Puerto Rico, which is in excess of 300
years old, will require 3000 analyzes. The last sample will be collected from the eastern margin of the Bahamas. We have located a suitable core which we estimate to be 150 years in age. In addition we will analyze the remaining corals at an annual resolution. This will enable us to show long term trends in geochemical proxies from a number of corals over a wide latitudinal range.

◆ **Strontium and magnesium concentration:** The strontium concentration will be determined in order to remove the influence of temperature on the oxygen isotopic composition. The number of samples involved will be similar to that estimated for the stable isotope work. We have recently published a calibration for Sr/Ca vs. temperature in *Montastraea faveolata* and this species behaves similarly to other corals from the Pacific (Swart et al., 2002c). We will attempt to use the Mg concentration of corals as a paleotemperature indicator (Mitsuguchi et al., 1996). Barium will be determined using the ICP-OES at the same time as the Mg and Sr are measured. As the Sr/Ca record will be an indicator of temperature (temperature at all sites in the Lesser Antilles appears to behave coherently) we will be able to use this indicator in conjunction with the density bands to refine the age dating of the samples.

◆ **Relationships between oxygen isotopes and salinity:** A critical component in this study is the establishment of the relationship between salinity and the $\delta^{18}$O of the water. Although there have been no extensive studies between these two parameters in these regions of the ocean, it is fortunate that a salinity monitoring program has been in effect in cooperation between W. Johns of RSMAS and D. Wilson. We have already taken advantage of this program and obtained a series of samples throughout the region which have established a relationship between salinity, oxygen, and carbon isotopes. We will continue to take advantage of opportunities to measure the stable O isotopic composition of water samples. Of particular relevance is the collection of fortnightly samples during cruises through the northern portion of the region by the Explorer of the Seas (Williams and Prager, 2002; Swart et al., 2003).

◆ **Coral Core Collection:** We have collected coral cores from most of the Windward and Leeward Islands. As a result of the timing of the trip and limited resources we were not able to spend sufficient time at each island to locate the ‘best’ material. In addition we did not collect material from the Bahamas or the Turks and Caicos. In order to extend our latitudinal transect we request ten days of ship time to collect material from Bahamas and Turks and Caicos. This particular location is important to this study as it will sample water from the sub-tropical Atlantic gyre and it is outside the TNA area (Figure 1). As salinity in this area should be correlated with the TSA, a long term record from this area will show an increase in salinity as suggested by Curry et al. (Submitted).

◆ **X-radiography & Densitometry:** We propose to measure coral growth parameters on the each of the possible cores from the CASE 02 cruise. This will first provide an age chronology independent of isotopic or chemical signals to guide sampling. The density band record as revealed on X-radiographs will be further processed to determine extension, density, and calcification parameters. Finally, the absence of an individual annual signal when comparing density bands and isotopic data may be indicative of a climatic event not identified in the corresponding record. For example, a single missing density band can go unnoticed; however, in comparison with isotopic records, the absent band may indicate the influence of biological factors such as bleaching, disease, or other such stressors that affect skeletal accretion. This will be extremely useful not only for cross-dating individual coral chronologies but also for verifying the integrity of the chronologies and the cause(s) of potential anomalies. Coral cores will be sectioned and X-radiographed to reveal the quality and length of the annual density-band record from which appropriate cores will be chosen for isotopic and elemental analysis.
Figure 9: Replicate analyses of standards in the University of Miami laboratory which show for these particular runs a RSD for Sr/Ca of 0.08% and a 1σ for O of 0.04‰. These values are the best we have obtained and realistically we quote values of 0.3 for Sr/Ca and 0.08‰ for O.

Equipment and Facilities

The X-radiography analyzes will be carried out at Nova Southeastern University. Nova Southeastern has a well-equipped X-radiography facility and the PIs have successfully worked together on many other projects. Geochemical analyzes will be carried out at the University of Miami and the University of South Floida. The University of Miami Stable Isotope laboratory has state of the art mass spectrometers, including a MAT 251 and Delta plus dedicated to carbonate analyzes and two Europa mass spectrometers, one used for hydrogen and oxygen isotopic composition of waters and compound specific analyzes and the second used for the measurement of stable isotopes in organic materials. The University of Miami also has a unique device for measuring fluorescence (Milne and Swart, 1994). Miami has recently purchased a Varian ICP-OES and this is now operational, routinely producing Sr/Ca analyzes with a precision of < 0.3 RSD. The University of South Florida is also equipped with a Delta-plus and Kiel device as well as a Perkin Elmer ICP-OES. Similar precision is available at both facilities. In order to address the issue of precision raised in a previous version of this proposal we enclose two recent runs on our stable isotope mass spectrometer and ICP-OES instruments at Miami. The data from 40 consecutive analyzes of our internal laboratory standard on our mass spectrometer and our ICP-OES show external precisions of 0.04 ‰ and 0.08 % (RSD) respectively (Fig. 10).

Personnel

The project is a joint project between six researchers at four different universities. The work will be supervised by Dr. P.K. Swart at the University of Miami. Dr. Swart has extensive experience in working with both stable isotopes and minor elements in coral skeletons. Initial work on the project will be the responsibility of Chris Moses, a Ph.D. student with Dr. Swart working on corals from Cape Verde. A second student is anticipated to join the project in 2003. Dr. R.E. Dodge and Ph.D. graduate student K. Helmle at Nova Southeastern University will participate for X-radiography, densitometry, sampling strategies, and data interpretation. They have long experience with coral skeletal radiographic and densitometric analysis. Dr. Quinn has extensive experience using the geochemistry of coral skeletons to reconstruct climate variability. Most of Quinn's past work has featured Pacific corals, but he has recently been funded by NSF to work on Atlantic corals. A portion of this project will form the basis of the PhD studies of a graduate student at USF. Dr. A. Winter will provide the coral from Puerto Rico for this project and assist in the interpretation. Dr. Winter is currently a program manager at NSF and will take...
no support from this proposal. Dr. Winter will also recuse himself from any involvement in decision making processes on this proposal. Dr. D. Enfield from NOAA/AOML will assist in data interpretation at no charge to the project. Dr. Mestas-Nuñez who has been involved in studies on Atlantic climate will also participate in the project. Dr. A. Clement will be involved as a liaison between Geology and the Climate dynamics aspects of this proposal. She will be involved as a committee member on Chris Moses thesis and will jointly supervise a new Ph.D. student who will work on the project. Finally integration into HYCOM will be accomplished in conjunction with Dr. E. Chassignet in the division of Meteorology and Physical Oceanography at RSMAS.

**Significance**

This proposal offers an umbrella under which work involving proxy indicators of climate within the Atlantic can be considered. There is abundant evidence that thermohaline circulation (THC) (Bond et al., 1993; Broecker, 1997) and hence salinity balance in the Atlantic is directly implicated in climatic fluctuations on a decadal and millennial timescale (Bryan, 1986; Stocker and Wright, 1991; Rahmstorf, 1996; Schmittner and Clement, 2002). If salinity changes are able to persist for extended periods of time, then the possibility exists that climate variation in the tropics could significantly alter THC and influences patterns of climate. Such variations might be induced through extended periods of enhanced ENSO activity which are known to influence Atlantic salinity (Schmittner et al., 2000). Our collections will supply an extensive suite of core material through the strip-chart recorder area of the Caribbean which can be used for the analyzes of many other proxies of temperature, salinity, and circulation. Once the basic connections are established within this area, we anticipate that many other projects will be initiated by a variety of different groups to examine these proxies and to provide a retrospective look at water circulation within the Caribbean. Such information can be then used to constrain various circulation models which could be run for the time period for which adequate atmospheric data are available. The work in the Windward and Leeward Islands can then also be related to ongoing projects involving isotopic analyzes in corals from islands off the northern coast of Venezuela (Cole), Puerto Rico (Winter) as well as coral localities further into the Caribbean such as Belize, the Gulf of Mexico, the Florida Keys, the Bahamas, and Bermuda. A more direct history of the Atlantic temperature oscillation could be determined by measuring changes in corals in the TNA and TSA affected areas. We have conducted a preliminary study (White, 1995; Swart et al., 1998) in one of these areas, the Gulf of Guinea, and have a currently funded effort in the Cape Verde region.

**Educational and Outreach**

Some of the work in this proposal will be the subject of at least two Ph.D. dissertations at the Universities of Miami and Nova Southeastern. The material will also be used in a current outreach program in which Dr. Swart has participated annually since 1998. This program, known as INSTAR, involves teaching high school science teachers in current research projects. The products of coral reef research are a component of Project Oceanography, a live television program designed for middle school science students, which is run by the College of Marine Science at USF.