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# ***Seasonally-Resolved Records of Surface Ocean Conditions in Brain Coral from Bermuda***

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## **Introduction**

The prevalence of decadal/interdecadal variability in the North Atlantic Oscillation (NAO) is apparent in the modern instrumental record of sea level pressure (Hurrell 1995) and sea surface temperature (SST) (Sutton and Allen, 1997), and in proxy records derived from tree rings (Cook et al., 1997) and ice cores (White et al., 1996). Examination of the ocean's role in forcing this low-frequency variability is limited by the short duration and sparseness of the instrumental SST dataset, and the potential for instrumental biases caused by a methodology shift in the middle part of this century. Alternatively, high-resolution, multi-century long records of SST and sea surface salinity (SSS) can be constructed from geochemical analyses of the calcareous skeleton of hermatypic corals. In this paper we present a short, seasonally-resolved SST time-series constructed from stable isotope measurements of a brain coral (*Diploria labyrinthiformis*) collected on North Rock, Bermuda. Our results demonstrate the resolution and accuracy with which such proxy records can be built.

## **Why Bermuda ?**

Bermuda is an attractive site for our study for several reasons:

- Wintertime SST anomalies since 1950 show a strong positive correlation with NAO and this site is thus well-placed to index the sub-tropical gyre (Figure 1).
- It is the base for an ongoing (now 44-years duration), quasi-biweekly hydrographic station and is embedded in an area well-sampled by instrument-based SST measurements. Availability of high-resolution instrumented data is needed to maximize the validation potential of coral-based record at any site.

- Bermuda is home to several dome-shaped coral species which have been used successfully elsewhere for paleoclimate reconstructions. Further more, some Bermuda corals have extraordinary life spans approaching 1000 years, offering the potential for proxy records spanning the Little Ice Age and Medieval Warm Epoch.

## **Paleoclimate records from corals**

The calcareous skeleton of massive, hermatypic corals is an archive of environmental information and their use as climate proxies has increased rapidly over the past decade. As corals grow, chemical and isotopic tracers are incorporated into the skeleton in concentrations that are dependent on prevailing conditions of ocean temperature, salinity, productivity, circulation and riverine input. Corals have several features which render them uniquely suited to the study of decadal-scale climate variability over the past few hundred years. Skeletal growth is comparatively rapid (accretion rates up to 10 cm per year) and continuous, individual colonies may achieve extraordinary longevity (up to 1000 years) and many species are distributed across the global tropical and sub-tropical surface oceans. Furthermore, corals accrete annual bands of high-and low density skeleton which are revealed in x-rays as growth bands much like the rings of a tree. These provide a first estimate of the age of a colony and also allow us to match climatic events in the geochemical record to specific years or even seas.

Several established geothermometers have been applied to reef corals (e.g. oxygen isotopes, strontium/calcium ratios) and others have been developed specifically for use on coral skeleton (e.g. uranium/calcium and magnesium/calcium ratios). The oxygen isotope thermometer is based on a temperature-dependent fractionation of the  $^{18}\text{O}/^{16}\text{O}$  ratio (expressed as  $\delta^{18}\text{O}$ ) between water and the calcium carbonate skeleton of the growing coral. In general, the  $\delta^{18}\text{O}$  value of coral skeleton decreases by between 0.18 and 0.22 per mil for every  $1^\circ\text{C}$  rise in water temperature, and the relationship is linear over our range of interest (between  $7^\circ\text{C}$  and  $30^\circ\text{C}$ ) (McConnaughey 1989, Gagan et al., 1994). Skeletal  $\delta^{18}\text{O}$  is also influenced by the isotopic composition of seawater which, being a function of the hydrologic balance, is closely related to salinity.  $\delta^{18}\text{O}$  of North Atlantic surface water decreases by approximately 0.6 per mil for every per mil decrease in salinity (Craig and Gordon 1965). At Bermuda, the amplitude of the seasonal SST signal ( $6\text{--}8^\circ\text{C}$ , (IGOSS NMC - satellite- SST data for a  $1^\circ\text{C}$  grid square centered on  $32.2\text{N}$ ,  $64.5\text{W}$ , Joyce and Robbins 1996- hydrographic data) is equivalent to a  $\delta^{18}\text{O}$  range of 1.20 - 1.60 per mil. Seasonal surface salinity ranges from 36.40 to 36.56 per mil (Levitus - *World Ocean Atlas 1994*, Joyce and Robbins 1996, Joyce *per comm.*, 1998) contributing up to 0.10 per mil to the seasonal  $\delta^{18}\text{O}$  signal.

## **Development of an Oxygen Isotope SST record in Bermuda Coral**

The aim of our preliminary study was to devise a strategy with which to extract accurate seasonally-resolved SSTs from Bermuda coral skeleton. We emphasize seasonal resolution because the atmospheric and surface expressions of NAO are most strongly developed in wintertime data. We used monthly instrumented SSTs derived from two independent sources to calibrate our coral isotope thermometer over three full annual SST

cycles. Results of a previous attempt to recover seasonally-resolved SSTs from brain coral were problematic for two reasons: first, the annual range of isotope-derived SSTs was much smaller than is expected from equilibrium temperature-dependent isotope fractionation, and secondly, inter-annual variability in real SST was not replicated in the proxy SST time-series. Based on this study, Druffel (1989) suggested that *Diploria spp.* were unsuitable for seasonally-resolved paleotemperature reconstructions. We considered that this initial attempt may have been limited by an inappropriate sampling strategy adopted for the complexity of brain coral skeletal structure.

In July 1997, with the help of Drs. Sheila McKenna and Tony Knap (Bermuda Biological Station for Research) and Dr. Richard Dodge (Nova South-Eastern University), we acquired a small brain coral colony (*Diploria labyrinthiformis*) (Figure 2a) from the surface waters at North Rock, a site at the northern edge of the Bermuda platform. A 4 mm-wide slab was cut from the mid-section of the colony and x-rayed to reveal high and low-density band couplets (Figure 2b). Band counting and measurement of band width provide a minimum age of 70 years and an average annual linear extension rate of 2 mm for this colony (Richard Dodge, *personal communication*). Although low growth rate presents a challenge to high-resolution sampling, it indicates that colonies of 1-2 m in height are likely to contain 200-400 years of climate information.

Figure 2c is a simplified rendition of the skeletal structure of a single *Diploria* corallite adapted from Dodge et al., (1984). Each corallite houses a single living coral polyp in a colony of thousands of identical polyps. The corallite is a tube-like structure made up of several different skeletal elements. The walls of the corallite, the endothecae, are equivalent to the rim of the tube. Within the tube are a complex arrangement of vertical and horizontal structures which alternately support and impale the polyp tissue. Linear extension of the corallite occurs by accretion of new skeleton at the surface of all elements in the tube and at its rim. Although all elements advance linearly, continuously and probably at the same rate, the corallite surface is concave such that the skeleton within the tube is 2 mm lower than the same-age skeleton constituting the rim of the tube. Thus, in our colony, samples extracted across a single, horizontal growth band will consist of skeleton accreted at different times over a period of one year. To demonstrate how this might affect recovery of an accurate climate signal we measured the  $\delta^{18}\text{O}$  composition of samples extracted in a horizontal band within a single calyx (sample spots in Figure 2c). Samples for isotope measurements are extracted using a hand-held slow speed mini-drill fitted with a 0.5 mm, tapered diamond-tipped drill bit. Discrete powdered samples (30-50  $\mu\text{g}$ ) are loaded into stainless steel boats and introduced to an automated PRISM light isotope ratio mass spectrometer housed in the National Ocean Sciences Accelerator Mass Spectrometer (NOSAMS) facility at WHOI. The precision of the instrument, based on replicate standard measurements is 0.07 per mil for  $\delta^{18}\text{O}$ .

The range of isotope values across a single corallite is large, approximately 0.6 per mil which is equivalent to a temperature range of 3°C (Figure 2d). One reason for this high variability may well be the difference in age between samples. Samples from within the corallite tube consist of skeleton accreted several months before that in the adjacent wall. A sampling strategy which includes all (or a different combination of) skeletal elements in a single sample will not accurately resolve seasonal SST variability, a problem

observed by Druffel (1989). On the contrary, consistent isotope values were obtained from samples taken from the wall of the corallite (Figure 2d, encircled data points). This result is to be expected because the outer rim of the tube is isochronous in the horizontal plane. Based on these data, we constructed a short  $\delta^{18}\text{O}$  time-series from samples extracted serially from a single endothecal element. A continuous groove was drilled from the surface of the colony and sample powder collected at regular intervals (Figure 2b). The isotope data are plotted in figure 3, compared against the BATS SST record and the IGOSS NMC satellite-derived SST record from the winter of 1993/4 through the summer of 1997. The following observations are important:

- 1) The isotope SST record shows strong seasonal cycles, consistent with that evident in both instrumented datasets.
- 2) Inter-annual variability in the instrumented record over this short time period is well-matched by interannual variability in the isotope record.
- 3) Isotope values for samples at the top of the colony show increasing SST consistent with the colony having been collected in July just prior to the height of summer.
- 4) The observed amplitude of the seasonal isotope cycle (0.7 per mil) is less than half of what is expected from temperature-dependent equilibrium isotope fractionation (1.2-1.6 per mil) and is similar to that obtained by Druffel (1989).

Intra- and interannual variability in the isotope record is in excellent agreement with that in the instrumented record, despite the small annual range in  $\delta^{18}\text{O}$ . There are possible explanations for the low annual range which include biological effects on the isotope signal, sampling resolution and salinity effects (although the latter would result in a higher-than-expected seasonal amplitude). These factors will be investigated in greater depth as our study continues. This preliminary work has been successful in demonstrating the potential of corals as an alternative source of accurate and highly-resolved long-time series of ocean climate in the sub-tropical Atlantic.

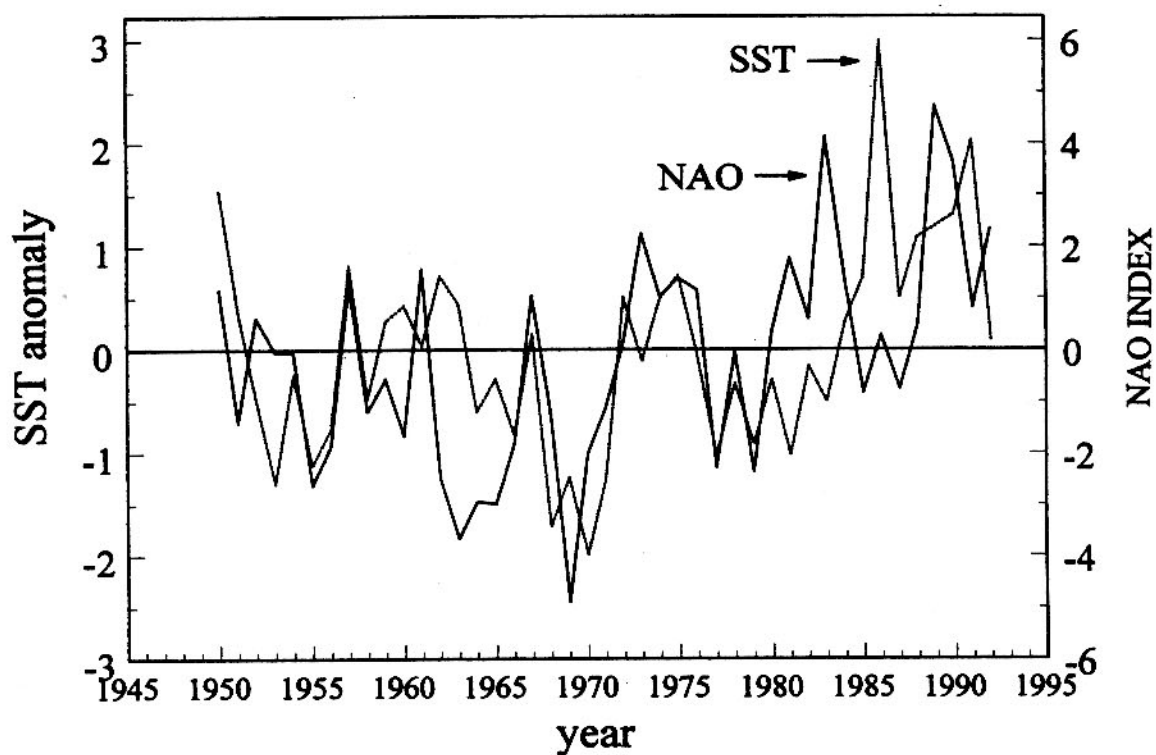
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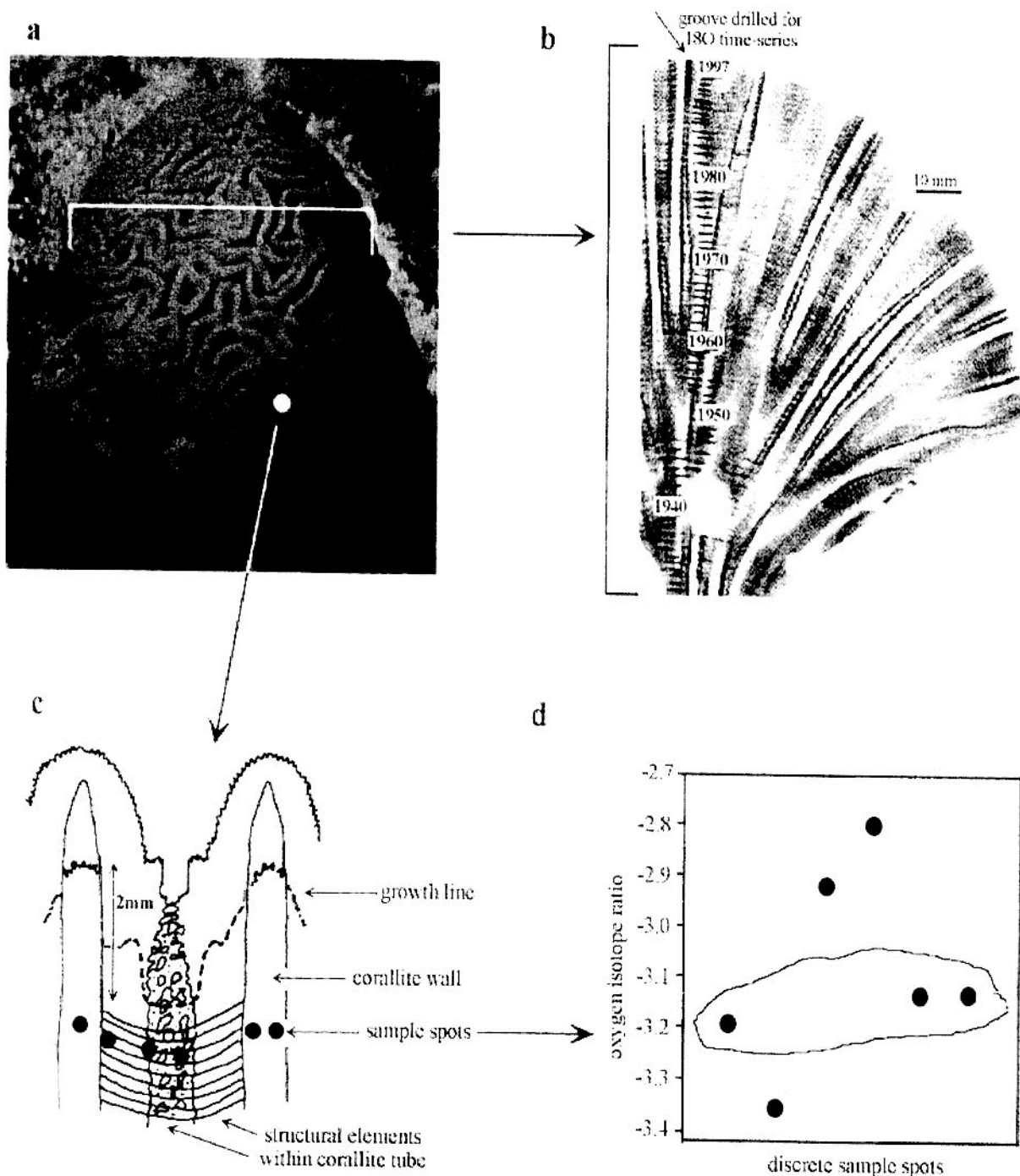
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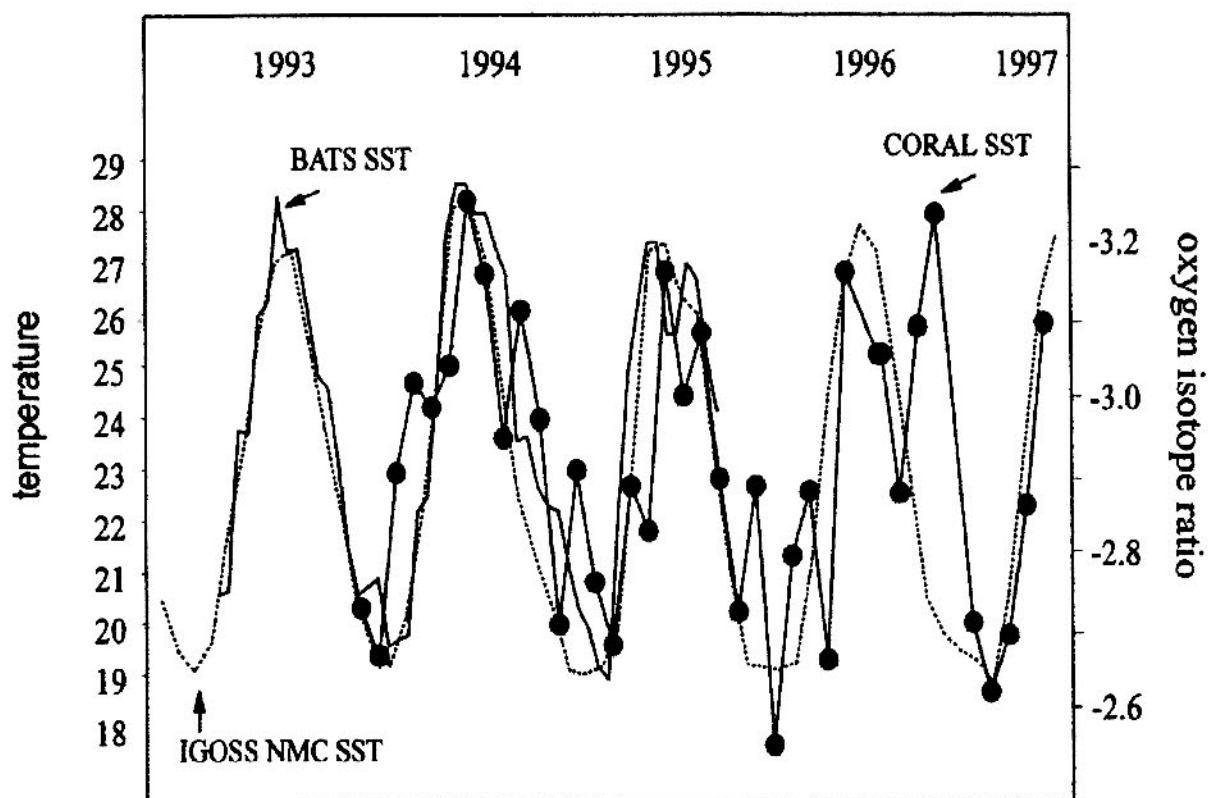


**Figure 1.** COADS February SST anomalies for  $2 \times 2^\circ$  grid square centered on Bermuda ( $32^\circ\text{N}$ ,  $64^\circ\text{W}$ ) show a strong, positive correlation with the NAO Index from 1950 through 1992.



**Figure 2.** *Diploria labyrinthiformis* colony at 15m depth, Jamaica (from Wood, 1991) (a), x-ray positive of the slab analyzed in this study showing annual light and dark density bands and age estimates based on band-counting (b), simplified sketch of a single *Diploria* corallite (not to scale; adapted from Dodge et al., 1984) showing relative position of individual skeletal elements referred to in the text and discrete sample spots for isotope analyses (c) and spread of isotope values obtained from discrete samples taken across a single corallite tube (d).





**Figure 3.** A seasonally-resolved SST profile constructed from the isotope analysis of Bermuda brain coral (solid line with markers) compared with BATS instrumented (fine solid line) and IGOS satellite-derived (broken line) SSTs at Bermuda between winter 1993 and summer 1997. Samples for isotope analyses were removed sequentially from a single endothecal element (shown in Figure 2b, c).