Monsoon Climate and Arabian Sea Coastal Upwelling Recorded in Massive Corals from Southern Oman

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Corals living in the coastal waters of southern Oman experience the influence of the seasonally reversing Asian monsoon system. The objective of the research reported here is to assess the potential for using the skeletal chemistry of these corals to investigate past variability in the monsoon climate. To this end, 20-year long, monthly resolution geochemical records are presented for cores from two massive Porites *corals, located 20 km apart near Marbat on the Arabian Sea coast of southern Oman. We consider four aspects of skeletal chemistry: oxygen and carbon isotopic composition, barium content and the nature and occurrence of annual fluorescent bands within the coral skeletons. Coral skeletal $\delta^{18}O$ documents variations in sea surface temperature which have regional and basin-wide significance. In particular, the $\delta^{18}O$ of coral skeleton precipitated during the period of the NE monsoon is strongly correlated with annual rainfall anomalies in India, whilst that precipitated during the period of the SW monsoon appears to provide information on variability in the strength of coastal upwelling. The stable carbon isotope composition and barium content of these particular corals display strong annual cycles, but do not appear to directly record interannual climatic/oceanographic variability. It is concluded that corals on the coast of southern Oman have great potential to provide high-resolution, century-long records of oceanographic and climatic variability associated with the operation of the monsoon climate system.*

INTRODUCTION

The climate and surface water oceanography of the Arabian Sea region are dominated by the seasonally reversing Asian monsoon. Strong, moist SW airflow in summer (the SW monsoon) alternates with weaker, dry and more variable NE airflow in winter (the NE monsoon). The SW monsoon, in particular, has widely recognised climatic, oceanographic and socio-economic significance (Fein and Stephens, 1987). It transports the moisture which falls as rain to feed most of the Indian subcontinent and the winds induce strong upwelling in the Arabian Sea waters. This marine upwelling triggers spectacular phytoplankton blooms, resulting in the region being one of the most productive areas of the world's oceans (Quasim, 1982). As a consequence of its perceived importance to a number of global and regional budgets (e.g., carbon, energy, moisture and fiscal), temporal variability in the strength of the SW

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monsoon has attracted considerable attention. For long time-scale variability (a few thousand years to a few million years), much of the current understanding on the nature and likely causes of interannual variability has come from analysis of deep-sea sediment cores retrieved from the Arabian Sea. These studies have recognised substantial variations in the intensity and character of the monsoon system through Quaternary glacial-interglacial cycles (Clemens et al., 1991), and integration of the geological data with climate models provides insights into the major physical controls (Kutzbach, 1981; Clemens and Oglesby, 1992). For the shorter time-scales (interannual to a few centuries), attempts to characterise and understand monsoon variability have traditionally concentrated on analysis of instrumental records. Extensive investigations of patterns of rainfall in India over the past 120 years (e.g., Parthasarathy et al., 1988, 1992) reveal some apparent relationships with other major climatic phenomena, such as the Pacific-based Southern Oscillation (Parthasarathy and Pant, 1985). However, the relationships appear to be complex and non-stationary, and the causes of monsoon variability remain poorly understood.

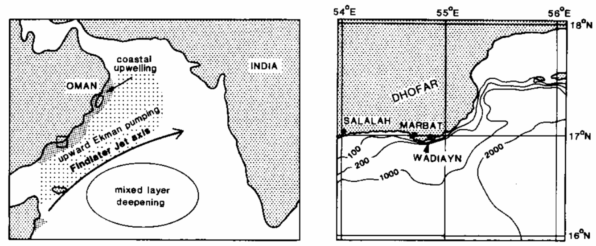


FIGURE 1—Left hand side: Location of the study area shown in the context of regions of open ocean upwelling (upward Ekman pumping) and coastal upwelling in the Arabian Sea during the summer SW monsoon period. The approximate location of the low level atmospheric Findlater Jet axis is also shown. The square box on the coast of southern Oman indicates the location of the map to the right. Right hand side: Location of the Marbat and Wadi Ayn sampling sites in the Dhofar region of southern Oman. The COADS SST data discussed in this study comes from the 2° latitude by 2° longitude box centred on 17° N, 55° E, i.e., from approximately the area of ocean depicted on the map. Isobaths are in metres.

One of the most promising ways forward in the effort to understand short-term climatic variability is the continued refinement of sophisticated computer models capable of simulating, on a global scale, the complex suite of ocean-atmosphere interactions that influence the monsoon circulation. However, the successful development of such models requires a time-space matrix of actual data on climatic variability over the time-scales of interest in order to constrain and test the models. Unfortunately, there are few oceanographic or land-based instrumental records greater than a few decades in length to provide this information for much of the Arabian Sea region. With these points in mind, the objective of the research reported here is to assess the potential of using annually banded massive corals living in the coastal waters of southern Oman to generate high-resolution and regionally significant records of Arabian Sea monsoonal climate and oceanography over the past few centuries. Before expanding upon the rationale behind the use of corals and the choice of field area, we provide further background information on the monsoon system and how it influences the Arabian Sea.

Arabian Sea Climatology

During the summer months of July–September, differential sensible heating over land and ocean results in low surface atmospheric pressure over Asia (centred on Tibet and northern India) and high surface atmospheric pressure at about 30° S over the southern Indian Ocean (Shea, 1986). This pressure gradient gives rise to a strong south to north airflow, which blows as a steady SW surface wind of about 15 m/sec over the Arabian Sea region (Hastenrath and Lamb, 1979). Moisture transported by the northward-flowing winds falls as precipitation over the Indian subcontinent, thereby releasing latent heat which acts to maintain and strengthen the pressure gradient and hence the strength of the airflow. During the winter months the pattern of differential heating reverses, and the Asian continent becomes colder than the oceans. Consequently, a cool, dry NE airflow develops over the Arabian Sea from about November to April. These NE monsoon winds are weaker (generally <5 m/sec at the ocean surface) and more variable than the summer SW monsoon airflow (Hastenrath and Lamb, 1979).

The SW monsoon winds drive a strong surface ocean current (the Somali current) across the Arabian Sea, and induce two forms of upwelling: open ocean upwelling and coastal upwelling (Smith and Bottero, 1977; Brock, McClain and Hay, 1992), (Fig. 1). Over the Arabian Sea, the SW winds are focused into a narrow low level jet (the Findlater or Somali Jet). Open ocean upwelling occurs within a 300 km wide region to the north-west of the jet axis as a consequence of Ekman pumping driven by strong positive windstress curl. The upwelling has vertical velocities of 1–2 m/day (Smith and Bottero, 1977) and influences shallow hydrography to depths of about 250 m (e.g., Brock, McClain and Hay, 1992). Coastal upwelling is driven by the offshore deflection of surface waters by Ekman transport. This upwelling affects the shallow hydrography up to depths of about 400 m (Brock, McClain and Hay, 1992), and occurs in a region extending from the coast to 150 km offshore and along some 1000 km of the Arabian coast. Both forms of upwelling bring nutrients to the photic zone which promote extensive and intense phytoplankton blooms (e.g. Brock et al., 1992). The combined effects of upwelling of cool subsurface water, lateral influx of cool water *via* the Somali current and evaporative cooling due to strong winds more than offsets solar gain and results in lowest annual sea surface temperatures (SST's) in August over much of the Arabian Sea (Prell and Streeter, 1981). During the NE monsoon, surface current flow reverses, and a winter temperature minima in SST is attained in January. There is little upwelling associated with this weaker NE monsoon flow. Warm SST's occur in the spring and autumn transition periods between monsoons.

In the time domain, there is considerable evidence for variation in the strength and position of the SW monsoon Findlater Jet leading to interannual variability in upwelling (e.g., Luther, 1991; Brock and McClain, 1992). Cadet and Diehl (1984) commented on decadal variability in the summer monsoon. They identified the mid-1950's to mid-1960's as having relatively high summer monsoon rainfall in India coinciding with shallow thermocline and cool summer SSTs in the Arabian Sea, compared to the mid-1960's to 1970's. Shukla (1987) and Rao and Goswami (1988) identified correlations between Arabian Sea SST and Indian summer monsoon rainfall, and noted that these correlations went through a change of sign from positive in the pre-monsoon months to negative in the post-monsoon months. That is, anomalously heavy Indian monsoon rainfall tended to be preceded by anomalously warm SST, and followed by anomalously cool SST in parts of the Arabian Sea. More recently, Tourre and White (1995), suggested, on the basis of their analysis of upper ocean temperatures for the period 1979–1991, the presence of an ENSO-style phenomenon in the Indian Ocean. They suggested that the early stages of each warm event manifested as positive SST anomalies in the Arabian Sea which then propagated equatorward and eastward through time to produce a variability similar in magnitude and timing to the Pacific ENSO.

Rationale and Objectives

Corals as Environmental Recorders

As they grow, corals record in the chemical composition of their skeletons information on the surrounding physical, chemical and biological environment. Since some varieties of massive corals develop colonies which live for several centuries and grow at rates of 10–20 mm/year, it is possible to extract climatic and oceanographic records ideally suited to investigating the nature of seasonal-century time-scale variability. Of relevance to the study reported here are four aspects of coral composition: stable oxygen isotopes, stable carbon isotopes, barium, and fluorescent compounds.

The most common use of oxygen isotopes in corals has been to obtain estimates of past seawater temperatures (e.g., Druffel, 1985; Shen et al, 1992; Dunbar et al., 1994). This is feasible due to a strong temperature dependence on the fractionation of the isotopes between water and the coral skeletal aragonite (e.g., Weber and Woodhead, 1972; Fairbanks and Dodge, 1979; Weil et al., 1981). For massive *Porites* corals (the genera used in our study), empirical estimates of this relationship based on comparison of annual ranges in skeletal $\delta^{18}O$ and SST have yielded values of 0.18 to 0.21‰ $\delta^{18}O$ (PDB)/° C, with coral isotopic composition becoming isotopically more negative with increasing temperature (McConnaughey, 1989; Gagan et al., 1994; Chakraborty, 1993). These values are close to the 0.21‰ $\delta^{18}O$ (PDB)/° C slope predicted on the basis of equilibrium precipitation at 25° C (Epstein et al., 1953; Craig, 1965), despite the fact that in *absolute* composition, reef-building coral skeletons are substantially out of equilibrium with the water from which they precipitated. For the successful reconstruction of past SST from coralline $\delta^{18}O$, variations in seawater isotopic composition, (for example, due to heavy rainfall or to extreme evaporation of restricted water bodies) must be minimal, or known. In addition, since there is evidence for kinetic isotope fractionation, corals displaying slow growth rates (<5 mm/year), or extreme variations in growth rate, should be avoided (McConnaughey, 1989; Allison et al., 1996).

The carbon isotopic composition of coral skeleton is dependant on a large number of factors. These include the isotopic composition of dissolved bicarbonate in seawater, the photosynthetic activities of the coral's algal symbionts and the contribution of respired CO_2 to the pool from which the coral draws its bicarbonate for calcification (e.g., Swart, 1983), coral growth rate (e.g., McConnaughey, 1989) and coral reproductive state (e.g., Gagan et al., 1994). Nonetheless, a strong annual cycle is often present, apparently associated with sunlight and related photosynthesis by the coral's algal symbionts (e.g., Fairbanks and Dodge, 1979).

Barium can be incorporated into the growing coral skeleton by substituting in place of calcium in the aragonite lattice. Lea et al. (1989) demonstrated that the uptake of barium into the lattice of 3 genera of corals was proportional to local seawater composition, with a distribution coefficient (D = Ba/Ca (coral)/Ba/Ca (seawater)) of approximately 1.3. This work suggested that corals could provide a quantitative record of past seawater barium composition. Using the fact that barium usually has a nutrient-like vertical profile in the oceans (depleted at the surface, enriched at depth), Lea et al. (1989) illustrated how corals living in regions of upwelling could be used to generate records of past upwelling intensity.

Fluorescent banding in coral skeletons was first described by Isdale (1984) from *Porites* corals on the Queensland shelf. Isdale noted that this banding was annual and that there was a marked correlation between the intensity of fluorescence and the flow of the large Burdekin River, and this lead him to suggest that fluorescent bands in corals could be used to provide records of past rainfall. Boto and Isdale (1985) and Susic et al. (1991) went on to demonstrate that much of the fluorescence in the coral skeletons came from terrestrially derived humic compounds, washed into coastal waters during periods of rainfall and run-off and subsequently incorporated into the growing coral skeleton. Although this correlation between rainfall/run-off and fluorescence clearly holds for some regions in addition to Australia (e.g., Papua New Guinea; Scoffin et al., 1989), unexplained discrepancies are apparent in other areas (e.g., south Thailand; Scoffin et al., 1992).

Objectives and Approach of this Study

The objective of this study is to test the hypothesis that corals on the coast of Oman can yield records of regional oceanographic variability that could be useful in understanding the operation of the monsoon system. To this end, comparisons are made between high-resolution geochemical records of the past 20 years derived from analysis of cores collected from two corals situated 20 km apart. This allows assessment of the extent to which variability in skeletal composition is of regional environmental significance, as opposed to being of purely local or colony-specific significance. Comparison of the coral records with nearby SST data and with an index of rainfall variability in India allows us to further explore the regional significance of the coral records.

Our original hypothesis was that we would be able to reconstruct variability in SST using coral skeletal $\delta^{18}O$, and variability in the intensity of coastal upwelling through analysis of skeletal barium. The utility of skeletal oxygen isotopic composition as a measure of SST variability in the Oman region rests upon the combination of extremely low regional rainfall and lack of permanent rivers or streams in the hinterland, the unrestricted nature of the coastal Arabian Sea waters and the large SST variability known to occur seasonally. These factors suggest that changes in the oxygen isotopic composition of seawater (due to rainfall, evaporation or mixing of different water bodies) would likely be small compared to the temperature-induced isotopic signals in the coral skeleton.

FIELD AREA, MATERIALS AND METHODS

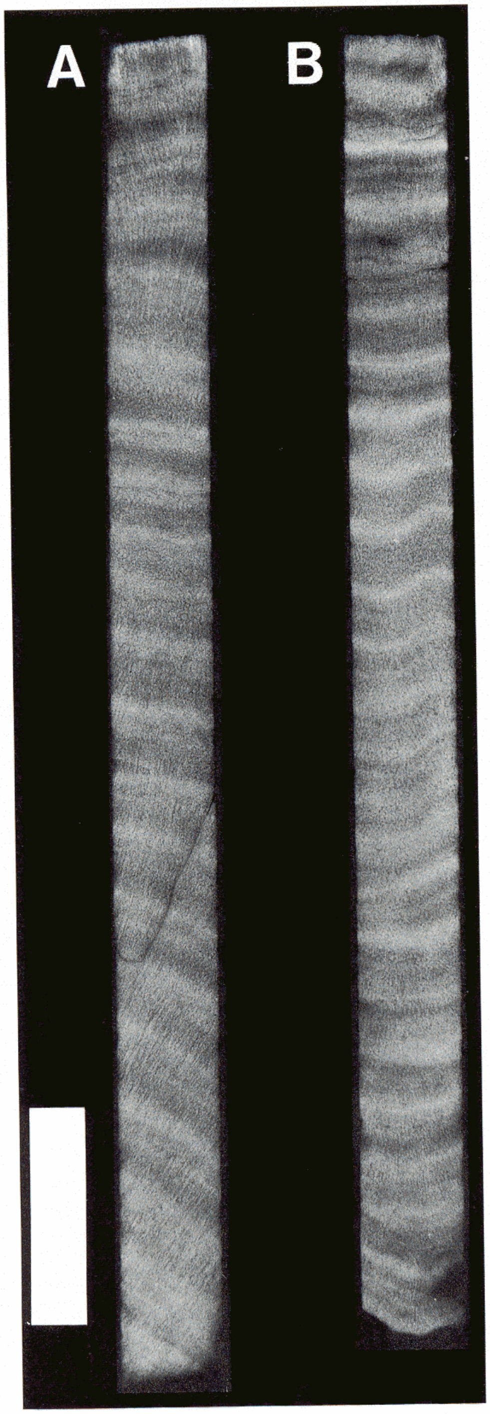
Coral material was collected from two sites in the vicinity of Marbat in the Dhofar region of southern Oman (Fig. 1). Three factors lead to the choice of site. First, it is located in a region strongly influenced by SW monsoon coastal upwelling (Currie, 1992). Second, the continental shelf is narrow (<2 km), and hence shallow-water shelf effects on SST are likely to be at a minimum. Third, there are large (>1 m diameter, >100 years old) massive *Porites* corals living at several locations along the coast. In this region, upwelling of cool, nutrient-rich waters during the summer monsoon leads to the seasonal prolific growth of frondose macroalgae, including the endemic brown *Sargassopsis zanardinii* and the kelp *Ecklonia radiata* (Barratt et al., 1984). The composition and occurrence of coral communities in Oman are well described by Salm (1993) and Glynn (1993).

Coral sampling (by hand-held corer) took place in early October 1992 at a site near the town of Marbat, and at a site near Wadi Ayn, 20 km east of Marbat (Fig. 1). At Marbat the cored coral was in the middle of a small (300 m wide), open embayment, fully exposed to the open-shelf waters. At Wadi Ayn the coral was in the mid-region of an elongate (250 m long), narrow (100 m wide) embayment, considerably more sheltered from open-shelf waters than Marbat. At both sites, cores (300–310 mm long) were retrieved from 1.2 m diameter, massive, yellow-brown pigmented *Porites* colonies in 4 m water depth.

Treatment, Subsampling and Analysis

Immediately following collection, the tops of the cores were treated with commercial bleach to remove coral tissue. On return to the laboratory, cores were cut to produce 5 mm-thick slabs which were treated with bleach again (to remove any residual coral tissue) then rinsed, dried and photographed under longwave (360 nm) ultraviolet light to record fluorescent banding in the skeletons (Fig. 2). Subsampling of each core was achieved by first cutting a 5 mm square rod down the length of the core slab. Then, a hand-held miniature circular saw (blade thickness 0.2 mm) was used to cut this rod into equally spaced growth increments. In the Marbat coral, the cut-spacing was every 1 mm, whereas in the Wadi Ayn coral it was every 1.25 mm down the rod edge for the top 205 mm of the core, then 1.5 mm for the remainder. The sample spacing was chosen to yield approximately 12 samples/annual growth increment. All saw cuts were made perpendicular to the local growth axis to ensure optimum subdivision into growth increments. The small corallite size in massive *Porites* corals results in the main zone of calcification (at the outermost edges of skeletal elements) occupying a vertical distance of only about 0.5 mm at any point in time. This fact, combined with our sampling style, will introduce a (relatively small) degree of time-averaging, and hence smoothing, of the coral record. Any additional calcification through the thickness of the tissue layer (about 9 mm in our corals when collected, which is exceptionally deep) would result in some additional time-averaging of the coral record (Barnes and Lough, 1993; Barnes et al., 1995; see Results for further discussion). Following stable isotope analysis of the samples (see below), a chronology for each core was developed using the strong seasonal cycle present in the $\delta^{18}O$ records. The isotopically most positive sample in each year was taken as representing the SW monsoon minimum SST and was allocated a date of mid-August in that year (based on the modal minimum SST month in nearby instrumental SST records, see Results section below). This procedure revealed the Marbat record to be 23.7 years in length (mean of 12.2 samples/year) and the Wadi Ayn coral record to be 19.9 years in length (mean of 11.5 samples/year). Linear interpolation between SW monsoon peaks was used to allocate a date to each intervening sample. To facilitate comparison between coral and other climate data, the TIMER program (ARAND software, courtesy of Phil Howell, Brown University) was used to develop records at equal, monthly, time-steps.

Oxygen and carbon stable isotope analyses were performed on crushed 0.5–1.0 mg subsamples. The coral powder was reacted with 100% orthophosphoric acid at 90° C in an automatic carbonate preparation system, and the resulting CO_2 analysed on a VG Isogas Prism mass spectrometer. The standard deviation for 62 analyses of a coral powder (COR1B) run as a sample over the 15 month period during which analyses were performed was ±0.05‰ for $\delta^{13}C$ and ±0.10‰ for $\delta^{18}O$. All carbonate isotopic values have been corrected for isobaric interferences and are quoted relative to PDB.



Coral Ba/Ca was measured by inductively coupled plasma mass spectrometry (ICP-MS) *via* a combined internal standard-isotope dilution technique (Lea and Boyle, 1993; Lea and Martin, submitted). Prior to analysis for barium, 1–3.5 mg subsamples were cleaned to remove surficial contamination (Lea and Boyle, 1993). Briefly, coral material was first broken into coarse silt-to-medium sand-sized pieces in an agate mortar and pestle. The resulting samples were repeatedly oxidised to remove organic matter (with either boiling in a 50:50 mix of 30% hydrogen peroxide:0.21 N sodium hydroxide, or, soaking for 24 hours in 5% sodium hypochlorite) and etched with 0.006 N nitric acid, with multiple rinses in deionised water. Etching was designed to remove 5–6% of each sample. Coral fragments were transferred to acid-leached vials prior to the final etching and rinsing steps. Cleaned samples were dissolved in a 0.13 N nitric acid spike containing gravimetrically calibrated concentrations of ^{45}Sc and ^{135}Ba. Ratios of ^{45}Sc/^{44}Ca and ^{135}Ba/^{138}Ba were determined on a Fisons/VG PlasmaQuad 2+ ICP-MS using dual-mode acquisition and final Ba/Ca ratios were calculated by reference to spiked gravimetric standards ("SGS"). Reproducibility of Ba/Ca ratios is estimated at $\pm$0.8% (1 sigma) based on 72 analyses of a matched consistency standard ("CS4").

Coral data are compared with the monthly Comprehensive Ocean Atmosphere Data Set (COADS) SST record for the 2° square centred on 17° N, 55° E (Fig. 1). To facilitate comparison between records, missing SST data (1 month in 1974, 2 months in 1972 and 3 months in 1971) were filled by inserting the mean value for the preceding and the succeeding years for that particular month. Statistical comparison of our records only includes the period 1973–1991, and, therefore, only 1 month with missing data. As a first step towards investigating the relationships between the coral data and more distant manifestations of the monsoon system, we compare our records with a composite index of rainfall anomalies compiled from 15 Indian meteorological stations in the box bounded by 15–25° N, 70–85° E (data extracted from the World Climate Disc originating from the Climatic Research Unit, University of East Anglia; stations listed in Appendix). This geographic region broadly coincides with the area of India where SW monsoon rainfall dominates the annual total. The anomaly values are annual deviations (expressed as a percentage) with respect to a 1968–1988 (inclusive) reference period.

RESULTS

Oxygen Isotope Composition

Results of oxygen isotope analysis are presented in three sections. First, observations are made on the overall

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FIGURE 2—Fluorescent banding in core slabs from the Wadi Ayn (A) and Marbat (B) *Porites* corals. Photograph taken under longwave (360 nm) ultraviolet light. Scale bar = 50 mm.

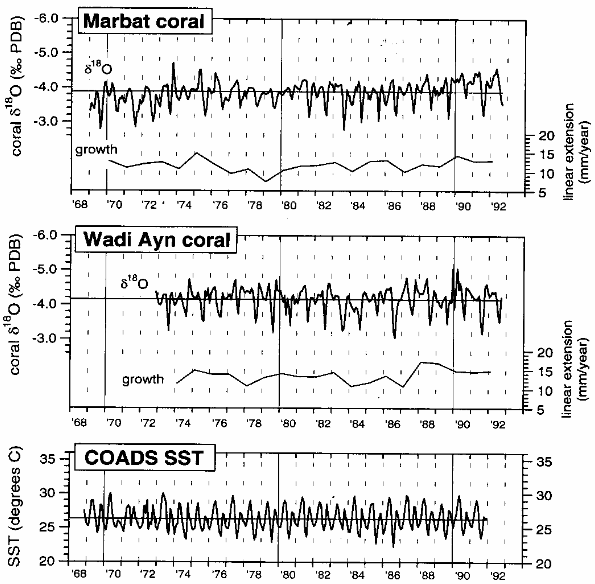

FIGURE 3—Monthly coral $\delta^{18}O$ and annual linear extension rate for Marbat and Wadi Ayn corals compared with monthly SST from the COADS dataset. Mean values for the period 1973–1991 inclusive are shown as thin horizontal lines.

nature of the coral isotope records, including the results of spectral analysis to investigate variation in the frequency domain. Next, the nature of the mean annual cycle in $\delta^{18}O$ for each of the corals is considered and compared with the mean annual cycle in COADS SST. Finally, the nature of interannual variations are explored in more detail, making comparisons with COADS SST and Indian rainfall data. All estimates of the temperature significance of variations in coral skeletal $\delta^{18}O$ are based on an assumption of a 0.21‰ $\delta^{18}O/°$ C relationship (cf., Epstein et al., 1953; Craig, 1965).

General Character of Coral Records

Stable oxygen isotope records for the Marbat and Wadi Ayn coral are presented in Figure 3 where they are compared to the COADS SST record and to skeletal linear extension rates measured from the cores. Visual inspection of these reveals the following principal features. Both corals display a strong seasonal cycle, with a double isotopic minima and double maxima. These features are expected if SST effects dominate the skeletal oxygen isotope variability of the records. On average, the Wadi Ayn coral is ca. 0.25‰ isotopically more negative than the Marbat coral. Although the mean linear extension rate for the Wadi Ayn coral is slightly greater than for the Marbat coral (13.6 mm/year vs. 11.6 mm/year respectively; 1973–1991 inclusive), this relatively small difference in growth rate is unlikely to be the main cause of the difference in mean isotopic composition between the corals (McConnaughey, 1989; Allison et al., 1996). Instead, it seems more probable that the difference is a reflection of the relatively sheltered location of the Wadi Ayn coral, with the effects of diurnal heating causing it to record a higher mean temperature.

The results of cross-spectral analysis (Fig. 4) confirm the similarity of the seasonal cycles in the coral and COADS SST records, with strong and coherent concentrations of variance at the 0.5 and 1.0 year periods (i.e., confirming the presence of the double maxima and minima each year). A weak concentration of variance at a period of 2.7 years in the Wadi Ayn coral record is not present in either of the other spectra and may be spurious.

Annual Cycle

Mean annual cycles for the period 1973–1991 inclusive for the coral oxygen isotope records and for COADS SST are presented in Figure 5. The coral records are similar to one another, and differences in isotopic composition between the two sites appear to be smallest during the SW monsoon period. This further supports the suggestion that the difference between the mean isotopic values of the corals is due to diurnal heating in the vicinity of the Wadi Ayn coral, greatest differential heating occurring during the periods of low wind speeds.

In both corals, the SW monsoon signal has an amplitude of 0.9–1.0‰ $\delta^{18}O$, which is about 80–85% of what would be anticipated from the 5.5° C SW monsoon cooling displayed in the COADS SST record. This substantial agreement supports the original hypothesis that SST is the main controlling factor on coral $\delta^{18}O$. The 15–20% attenuation of the coral signal is probably due to time-averaging of the coral record due to our sampling strategy and/or calcification in the tissue layer (see "Treatment, Subsampling and Analysis," above); small changes in water composition and/or differences in temperature between the coral sites and the COADS region could also be contributory factors.

The average NE monsoon cooling signal in the corals is about 0.2–0.25‰ $\delta^{18}O$, which is only about 30–40% of the magnitude anticipated from the ca. 3° C cooling observed in the COADS dataset. Although possible, it seems unlikely that the degree of time-averaging of the coral record due to patterns of skeletogenesis (Barnes and Lough, 1993; Barnes et al., 1995) would change dramatically on a seasonal basis. Therefore, the relative attenuation of the coral $\delta^{18}O$ signal for the NE monsoon is probably due to real differences in SST between the coral sites and the COADS region, and/or to changes in water isotopic composition.

Oceanographic cruise data indicate that spatial and temporal gradients in salinity off southern Oman are quite small, typically less than 0.4‰ over lateral distances of 100–200 km and water depths of 0–100 m; seasonal differences are confined to a similar range (e.g., Currie, 1992; Brock, McLain and Hay, 1992). Extremely low rainfall, the absence of any run-off (local or regional), the narrow and unrestricted continental shelf, and the remoteness of our coral sites from both the Red Sea and the Persian Gulf (two potential sources of high-salinity water) are the underlying reasons for this relative salinity homogeneity.

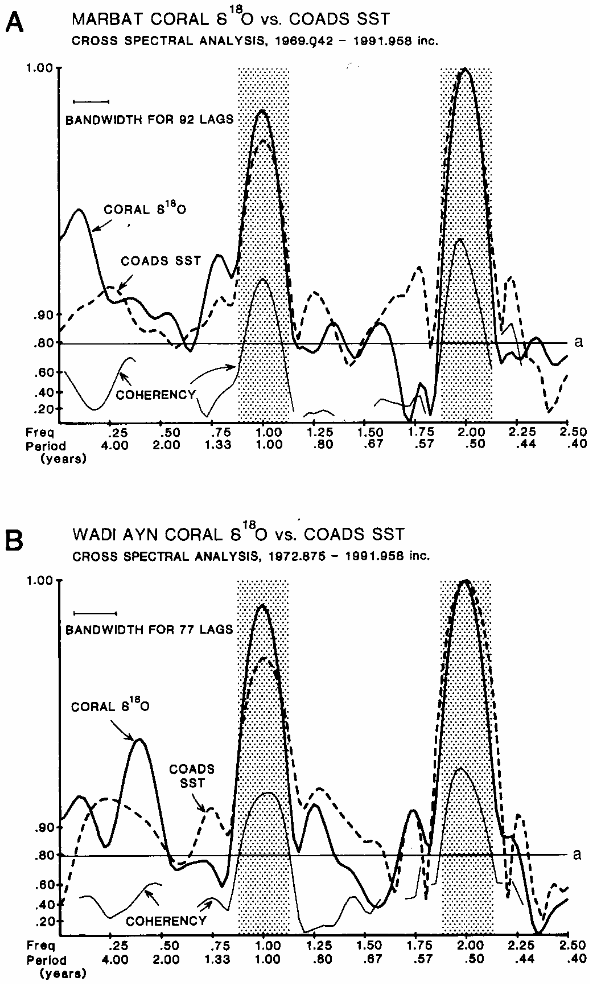

FIGURE 4—Cross-spectral plots for (A) Marbat coral $\delta^{18}O$ versus COADS SST for the time period 1969.042 to 1991.958 inclusive, and, (B) Wadi Ayn coral $\delta^{18}O$ versus COADS SST for the time period 1972.875–1991.958 inclusive. In each of these plots, variance is shown as a function of frequency for the coral and SST records (thick solid and thick dashed lines respectively). Coherency between the coral and SST records is indicated as a function of frequency by the thin (and discontinuous) solid line. The variance spectra are scaled from 0–1. The x-axis also indicates the coherency levels (the square of the coherency generally indicates the percent variance in common between the time series at any given frequency). The 95% confidence level for coherency is indicated by the horizontal line labelled "a". The strong, and coherent concentrations of variance at periods of 0.5 and 1.0 years have been picked out in stipple. The weak spectral peak at 2.7 years period in the Wadi Ayn coral record is not seen in either of the other datasets, and may be spurious. Spectral analysis performed using the ARAND software package, courtesy of Phil Howell, Brown University.

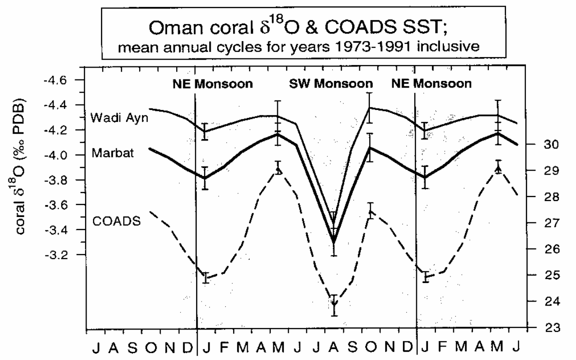

FIGURE 5—Mean annual cycle for the period 1973–1991 inclusive for Marbat and Wadi Ayn coral $\delta^{18}O$ and for COADS SST. Error bars indicate 95% confidence limits for selected months.

Based on the salinity versus seawater $\delta^{18}O$ relationship observed by Ganssen and Kroon (1991) in surface waters of the Red Sea, Gulf of Aden and adjacent Arabian Sea, it seems likely that 0.4‰ variations in salinity will be accompanied by less than 0.1‰ variation in water $\delta^{18}O$. Therefore, we believe that changes in water isotopic composition are unlikely to be a major factor in controlling the observed coral skeletal $\delta^{18}O$ signal. Turning now to SST variations. The sampled corals live immediately adjacent to the coast, whereas the COADS dataset was gleaned by ships, most of which would have stayed offshore. During the relatively low winds of the NE monsoon, it seems likely that there will be some coastal effect, resulting in reduced windspeed, and therefore less mixing and evaporative cooling, immediately adjacent to the coast. This rationale leads us to suggest that the main reason for the subdued coral $\delta^{18}O$ NE monsoon signal is a genuine difference between coastal and offshore SST development. Finally, we note that the positions and widths of peaks and troughs in the coral annual cycle records closely match those in the COADS SST record, which suggests that the assumption of uniform linear extension rate (implicit in the way we constructed our monthly chronology) was a reasonable estimate in the absence of detailed seasonal growth rate data.

Interannual Variability

To facilitate investigation of the nature and significance of interannual variations in coral oxygen isotope composition, mean annual values, mean SW monsoon values and mean NE monsoon values were calculated for each year of the coral and COADS SST records (Fig. 6). The SW monsoon season was taken as July to September inclusive, and the NE monsoon season as December (in year −1) to March inclusive, both time-frames chosen after consideration of the mean annual cycle (Fig. 5). The annual values are based on start November (in year −1) to end October. Linear regression analysis was used to explore correlations between coral records, COADS SST and the Indian

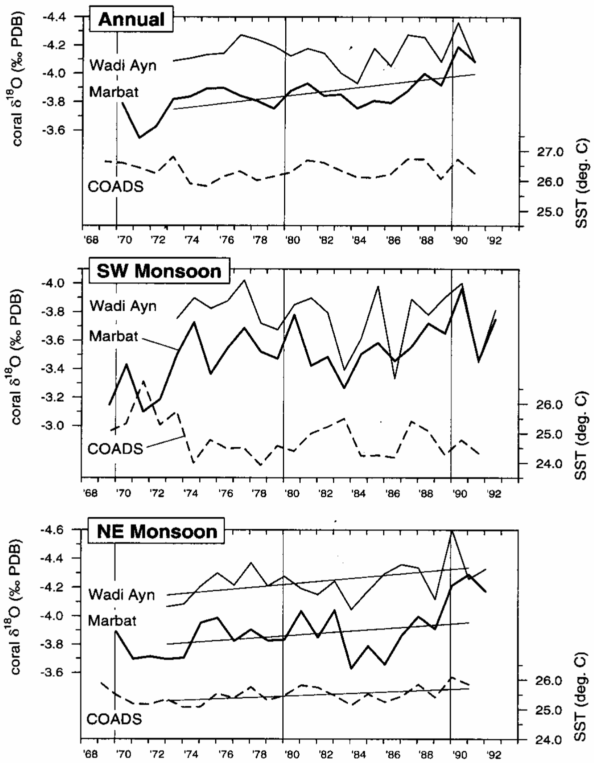

FIGURE 6—Coral $\delta^{18}O$ and COADS SST records for different time-divisions. Top panel is annual mean values (year = start November in year −1 to end October); middle panel is SW monsoon values (season = July to September inclusive); bottom panel is NE monsoon (season = December in year −1 to March inclusive). Values plotted opposite the season mid-point. Trends through time (>90% significance) over the period 1973–1991 inclusive are shown as thin black lines. In each panel, $\delta^{18}O$ and SST axes have been scaled such that a 0.21‰ increment is the same size as a 1° C increment in recognition of the established equilibrium relationship (Epstein et al., 1953; Craig, 1965).

rainfall index, and estimation of the significance of these correlations is based on calculation of Student's t (Table 1). In order to assess the contribution of unidirectional trends through time (as opposed to shorter time-scale variations) to correlations between data sets, 'detrended' time series were produced for the coral and SST records by subtracting linear trends. Linear regression analysis was then performed between these detrended time series (Table 1). All statistical comparisons between records, and calculation of trends, are based on the period 1973–1991 inclusive (the period of overlap of all records).

In general, interannual variability in coral $\delta^{18}O$ is about double what would have been predicted from COADS SST data. This discrepancy is particularly large (nearly 3 fold) during the NE monsoon season.

For annual mean values, the Marbat coral record shows a marginally significant (95% level) trend towards isotopically more negative composition, equivalent to a rate of temperature rise of about 0.5° C/decade. This trend is not apparent in the Wadi Ayn coral record or in the COADS SST time series. Although there are some visually identifiable similarities between the two coral records, these are only statistically significant (95% level) once the coral time series have been detrended. There are no significant correlations between coral and SST records. However, there is a significant correlation (95% level) between Marbat coral $\delta^{18}O$ and India rainfall anomaly. This correlation improves (to 99% level) once the linear trend is removed from the Marbat coral data.

For the SW monsoon season time series, there are moderately strong correlations (significant at 99% level) between the two coral records, but no significant correlation between the coral records and COADS SST or between the coral records and the India rainfall index.

In contrast to the annual and SW monsoon season data, there are strong correlations between coral and SST records during the NE monsoon period. There are two main features of these coral-SST correlations: (i) apparent trends in all time series, and (ii) similar shorter time-scale variability. All three records trend to values indicative of higher temperatures through time (95% significance for COADS SST; 90% significance for coral records). However, the rate of change of the coral $\delta^{18}O$ is about twice as fast (at about 0.1‰ $\delta^{18}O$/decade) as the rate predicted from the COADS SST trend (0.25° C/decade). Although these trends contribute to the level of significance of correlations between records, statistically significant correlations between the coral and SST records still persist once linear trends have been removed, implying that the two coral records and the instrumental SST record share similar short time-scale variability. Of the two corals, Marbat shows a significantly stronger correlation with SST. In addition, there is a particularly strong correlation between Marbat coral NE monsoon $\delta^{18}O$ and the annual India rainfall anomaly index, with isotopically more positive coral (i.e., inferred cool seawater) matching negative rainfall anomaly (i.e., relative drought). This correlation reaches a maximum of $r = 0.81$ (≫99.9% significant) when the linear trend is removed from the Marbat data (Fig. 7). Further exploration of this relationship, by comparison of NE monsoon Marbat $\delta^{18}O$ with monthly and seasonal Indian rainfall anomalies, reveals that the observed correlation was due mainly to variations in summer SW monsoon rainfall in India. The Wadi Ayn coral record shows a weaker, but still significant (95%) correlation with the India rainfall anomaly.

To summarise: of the three time-divisions considered (annual, SW monsoon and NE monsoon), the NE monsoon coral $\delta^{18}O$ record provides by far the best correlation with regional climate and oceanography. At the first level of interpretation, it suggests that NE monsoon coral $\delta^{18}O$ could provide a powerful index of past variations in regional SST and Indian rainfall. Although there are no significant correlations between coral and COADS SST records for the SW monsoon season, the fact that the correlations between the two coral records are as strong for that season

TABLE 1a—Results of linear regression of annual coral $\delta^{18}O$, COADS SST and India rainfall anomaly.

Original time series (1973–1991 inclusive)				Detrended coral and SST time series (1973–1991 inclusive)			
	Wadi Ayn $\delta^{18}O$	COADS SST °C	India rain (annual)		Wadi Ayn $\delta^{18}O$	COADS SST °C	India rain (annual)
Marbat $\delta^{18}O$	0.439 n.s.	−0.379 n.s.	−0.504 *	Marbat $\delta^{18}O$	0.463 *	−0.278 n.s.	−0.597 **
Wadi Ayn $\delta^{18}O$		−0.374 n.s.	−0.276 n.s.	Wadi Ayn $\delta^{18}O$		−0.364 n.s.	−0.277 n.s.
Marbat + Wadi Ayn		−0.444 n.s.	−0.276 n.s.	Marbat + Wadi Ayn		−0.378 n.s.	−0.500 *
COADS SST °C			0.003 n.s.	COADS SST °C			0.002 n.s.

TABLE 1b—Results of linear regression of SW monsoon coral $\delta^{18}O$ and COADS SST, and annual India rainfall anomaly.

Original time series (1973–1991 inclusive)				Detrended coral and SST time series (1973–1991 inclusive)			
	Wadi Ayn $\delta^{18}O$	COADS SST °C	India rain (annual)		Wadi Ayn $\delta^{18}O$	COADS SST °C	India rain (annual)
Marbat $\delta^{18}O$	0.615 **	0.256 n.s.	0.124 n.s.	Marbat $\delta^{18}O$	0.684 **	0.256 n.s.	0.127 n.s.
Wadi Ayn $\delta^{18}O$		0.012 n.s.	0.053 n.s.	Wadi Ayn $\delta^{18}O$		0.019 n.s.	0.542 n.s.
Marbat + Wadi Ayn		0.136 n.s.	0.094 n.s.	Marbat + Wadi Ayn		0.137 n.s.	0.094 n.s.
COADS SST °C			0.218 n.s.	COADS SST °C			0.218 n.s.

TABLE 1c—Results of linear regression of NE monsoon coral $\delta^{18}O$ and COADS SST, and annual India rainfall anomaly.

Original time series (1973–1991 inclusive)				Detrended coral and SST time series (1973–1991 inclusive)			
	Wadi Ayn $\delta^{18}O$	COADS SST °C	India rain (annual)		Wadi Ayn $\delta^{18}O$	COADS SST °C	India rain (annual)
Marbat $\delta^{18}O$	0.586 **	−0.742 ***	−0.724 ***	Marbat $\delta^{18}O$	0.495 *	−0.669 **	−0.808 ***
Wadi Ayn $\delta^{18}O$		−0.643 **	−0.476 *	Wadi Ayn $\delta^{18}O$		−0.553 *	−0.521 *
Marbat + Wadi Ayn		−0.784 ***	−0.692 **	Marbat + Wadi Ayn		−0.714 ***	−0.789 ***
COADS SST °C			0.376 n.s.	COADS SST °C			0.436 n.s.

n.s. Not sighificant
* Significant at 95% level.
** Significant at 99% level.
*** Significant at 99.9% level or greater.

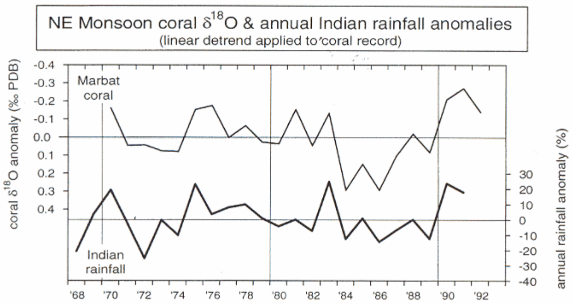

FIGURE 7—A comparison of our annual Indian rainfall anomaly index with the detrended Marbat NE monsoon $\delta^{18}O$ record. Both time-series are plotted opposite the mid-point of the year, with the NE monsoon period defined as December (year −1) to March inclusive.

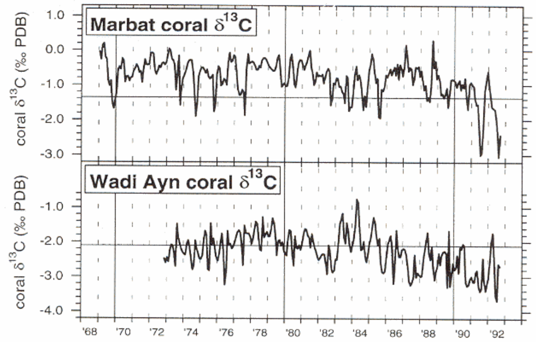

FIGURE 8—Coral $\delta^{13}C$ records at monthly resolution. The mean isotopic composition for the period 1973–1991 (inclusive) is shown as a thin horizontal line.

as for the NE Monsoon season indicates that the corals may still be recording significant environmental information. The importance of making a careful choice of coral sampling site is highlighted by the relatively poor performance of the Wadi Ayn coral (sheltered location) as a predictor of regional climate compared to the performance of the Marbat coral (exposed location). Finally, the interannual variations in coral $\delta^{18}O$ are about double that predicted on the basis of the COADS SST for both short timescale variability and unidirectional trends of warming, suggesting a strong sensitivity of the coastal waters to regional climatic and oceanographic forcing. Warming trends in SST appear to be concentrated in the NE monsoon season, but, possibly due to the previously inferred sensitivity of the coastal system, an apparent warming trend also exists in mean annual values for the Marbat coral record. Speculation on the reasons for the observed correlations, and on their wider applicability and significance, are reserved for the general Discussion.

Carbon Isotope Composition

Records of carbon isotope composition of both corals at monthly resolution are presented in Figure 8 (whole records) and Figure 9 (10-year period compared against skeletal $\delta^{18}O$, Ba/Ca and fluorescence). The Wadi Ayn coral is, on average, about 1.3‰ $\delta^{13}C$ more negative than the Marbat coral. Both corals display a large annual range (commonly >1‰) in $\delta^{13}C$ composition, with isotopically most negative values usually, but not always, coinciding with the peak of summer SST cooling as inferred from coral $\delta^{18}O$. In some cases, a secondary $\delta^{13}C$ minima occurs during the NE monsoon season. In terms of interannual variation, both records display a shift towards more negative isotopic values in the last 5–10 years. We have no good explanation for this trend. Although local rainfall records indicate some increase in SW monsoon rainfall over the past 20 years (from ca. 5 mm/month to 10 mm/month at Salalah; data courtesy of Phil Jones and Mike Hulme, University of East Anglia) it is hard to conceive of these small absolute changes in rainfall being related to sufficient change in cloud cover to cause the shifts in coral $\delta^{13}C$ *via* effects on symbiont photosynthesis. Surface ocean waters are known to have become, on average, isotopically more negative in $\delta^{13}C$ due to the effects of fossil fuel emissions; however, the magnitude and rate of change seen in the Oman coral records (about 1–1.5‰ $\delta^{13}C$ in 5–10 years) is somewhat greater than has previously been reported (0.4–1.0‰ $\delta^{13}C$ over the past 20 years; Quay et al., 1992;

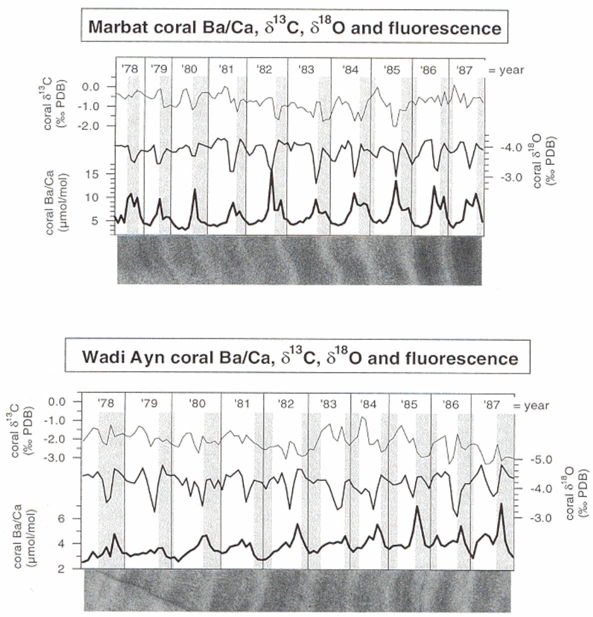

FIGURE 9—Comparison of coral $\delta^{18}O$, coral $\delta^{13}C$, coral Ba/Ca and skeletal fluorescence for the period 1978–1987 inclusive. The edge of the photograph next to the graphs is the line along which the coral was subsampled. The locations of brightly fluorescent bands have been extrapolated up from the photograph as shaded bars to aid comparison.

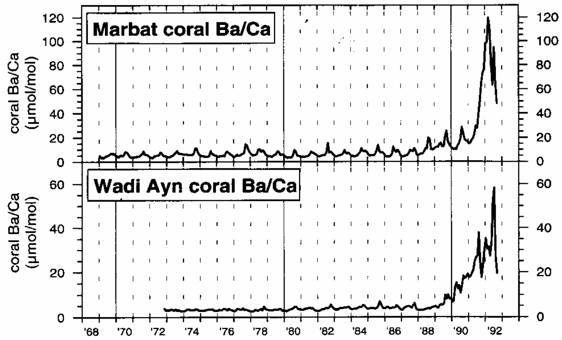

FIGURE 10—Coral Ba/Ca records at monthly resolution. The mean isotopic composition for the period 1973–1991 (inclusive) is shown as a thin horizontal line.

McNichol and Druffel, 1992; Broeker and Maier-Reimer, 1992). A similar magnitude of trend towards isotopically more negative $\delta^{13}C$ in a *Porites* coral from the Australian Great Barrier Reef has been reported by Aharon (1991), who noted that the trend was not matched in the $\delta^{13}C$ record from the shell of an adjacent *Tridacna* clam. In the Oman corals, comparison of records of mean annual $\delta^{13}C$, SW monsoon $\delta^{13}C$ and NE monsoon $\delta^{13}C$ did not reveal any significant similarities in interannual variation between the corals, other than those due to the trend towards more negative values. Therefore, the carbon isotope records suggest that the short time-scale $\delta^{13}C$ variability in one, or both of the coral records is dominated by local, or within-colony effects.

Barium Composition

Measurement of the barium content and salinity of surface water samples collected in October 1992 (the time of coral coring) yielded values of 41.4 ± 0.8 nmol Ba/kg seawater with S = 36.4‰ at Marbat and 42.3 ± 0.2 nmol/kg with S = 36.1‰ at Wadi Ayn. Applying the previously determined distribution coefficient between seawater and coral aragonite, D = (Ba/Ca (coral)/Ba/Ca (seawater)) = 1.3 (Lea et al., 1989) leads to an estimate of anticipated coral Ba/Ca of approximately 5 µmol/mol. Records of the actual Ba/Ca composition of Marbat and Wadi Ayn cores at monthly resolution are presented in Figure 10 (whole records) and Figure 9 (10-year period compared against skeletal $\delta^{18}O$, $\delta^{13}C$ and fluorescence). A dominant feature of both coral records is the large increase in Ba content towards the last few years of growth, which takes the Ba/Ca composition to well over an order of magnitude higher than anticipated. Below this outer zone of elevated levels, both coral records possess strong seasonality in barium content.

The extremely elevated barium content in the outer few years of growth in both cores, and the pattern of rapidly decreasing mean Ba contents with increasing age, suggests two possible explanations: 1) Ba is incorporated into the skeleton during growth in a phase(s) which decays gradually through time, releasing the excess Ba back into seawater; or, 2) elevated Ba levels could be an artefact caused by skeletal incorporation of Ba released from the tissue layer by bleaching. We tried a variety of modified cleaning techniques, including crushing the coral to a fine silt size prior to cleaning, increasing the number and intensity of the oxidation steps, and increasing the total proportion of the coral etched during the cleaning process, but all of these measures failed to significantly reduce the Ba/Ca values.

SEM examination of residual coral tissue in the outer few millimetres of the skeleton of the Marbat core (i.e., tissue not completely removed by the initial field treatment with bleach) revealed the presence of small (<1 µm) lozenge-shaped, barite crystals. This observation confirms elevated Ba content in the coral and/or algal symbiont tissue at the time of collection, although we have no indication of what phase the barium was in when the coral was alive. The ion probe technique and SEM were used to further examine the occurrence of Ba within the skeleton itself (i.e., after all coral tissue had been removed by strong oxidation). Imaging revealed elevated barium levels associated with sub-micron pores in the most recent few years of the coral core. Specifically, the barium was concentrated in pores between coral trabeculae and between individual aragonite fibres. These pores appeared to be constructional (i.e., left as holes during calcification) as opposed to being destructional (due, for example, to microboring fungi or algae). The identity of the barium-rich phase in these pores is still unknown, but if it is barite, then the crystal size must be less than 0.1 µm. Another possibility is that the barium is associated with organic matter, protected from the cleaning fluids by the sub-micron pore throats, but we have no direct evidence to support this suggestion.

At this time, the nature and significance of the elevated barium zones remain enigmatic. The fact that very high-amplitude seasonality occurs in part of the elevated Ba zone in both corals argues against the bleach-treatment artefact hypothesis since it would require highly selective skeletal incorporation of Ba released from the tissue. Therefore, the current weight of evidence tends to support the hypothesis of release through time of barium incorporated into the skeleton, in a phase distinct from aragonite (i.e., a refractory, slowly decomposing organic compound and/or barite), at the time of growth. These elevated barium levels are the subject of ongoing research which will be reported elsewhere (Lea and Tudhope, ms. in preparation 1996).

Below the extremely barium-rich outer few years of growth, both coral records display a distinct annual cycle in barium (Fig. 9). The Marbat coral has both a higher annual range and higher mean barium content (relative to age) than the Wadi Ayn coral. Annual barium maxima usually coincide with (Marbat) or lag by 1–2 months (Wadi Ayn) the peak of SW monsoon SST cooling (as inferred from skeletal $\delta^{18}O$). Barium maxima in the Marbat core frequently exceed 10 µmol/mol, a value that translates to seawater Ba concentrations of about 80 nmol/kg. Ba concentrations of this magnitude are only found in the Arabian Sea at water depths greater than 1000 m, an excessive depth for upwelled waters (Ostlund et al., 1987). Therefore, although the coral Ba records appear to document seasonal upwelling of nutrient-rich water, the Ba maxima may not only be a direct response to increased surface water Ba but might also reflect site-specific factors in coral-Ba incorporation such as inclusion of organically bound particulate Ba. Organically bound particulate barium ("bio-Ba") is known to be produced during phytoplankton blooms, and the flux of bio-Ba is closely correlated with the intensity of new productivity (Bishop, 1988; Dehairs et al., 1991, 1992; Stroobants et al., 1991).

With the exception of the trend to more elevated values through time, interannual variations in barium content do not appear to be correlated between the two corals. There are two factors which may account for the fact that coralline barium in the Oman coral do not record interannual variations in upwelling, as has been observed for corals from the eastern tropical Pacific (Lea et al., 1989; Shen et al., 1992). First, it may be that there are taxon-specific effects on the mechanisms of barium uptake into coral skeleton, and that the *Porites* corals used in this study are particularly influenced by coral tissue or algal symbiont regulation of barium, including the possible incorporation of productivity-related bio-Ba (see above). A second possibility is that the differences between the two Oman coral barium records are in some way related to the intensity of the seasonal upwelling in coastal settings, or to unique oceanographic factors for barium in this region.

Skeletal Fluorescence

Distinctive fluorescent banding is present in the skeletons of both corals (Fig. 2). This banding is similar in colour and intensity to that previously reported from regions with a demonstrable terrestrial organic source for most of the fluorophores (e.g., Australian Great Barrier Reef; Isdale, 1984; Susic et al., 1991). Comparison of the Oman coral fluorescence with skeletal $\delta^{18}O$ and Ba/Ca records (Fig. 9) indicates that the dominant banding is annual, and that bright band deposition usually occurs immediately following the SW monsoon, in the period from late summer to mid-winter or early spring. The arid nature of the adjacent Arabian landmass (rainfall ca. 100 mm/year at Salalah, no permanent rivers, and a paucity of terrestrial vegetation) make it hard to conceive of the coral fluorescence having a local terrestrial organic source. Lateral transport of terrestrial organic matter from more humid areas also seems unlikely given the large distances involved and the lack of correlation between bright fluorescence and either the SW monsoon or NE monsoon seasons (when significant surface current flow occurs). These factors, combined with the coincidence of intense skeletal fluorescence with the peaks (or just after peak values) in coralline barium, leads us to speculate that the fluorescence is associated with deposition or breakdown of marine organic matter. In this scenario, bright fluorescence could be related to the planktonic component of seasonal productivity and/or to the prolific macroalgal biomass which decays over a period of weeks–months in the autumn. The change in colour of fluorescence between "bright" bands (yellow) and "dull" bands (bluish) need not necessarily imply the presence of different types of fluorophore, but could simply be related to variable effects of quenching and energy transfer processes on different concentrations of the same fluorophore(s) (Matthews et al., in press). Further investigation of the fluorescence spectra from these corals may yield more information on the nature and possible sources of the fluorophores.

DISCUSSION

Of the four discussed environmental tracers, the stable oxygen isotope composition of the skeleton appears to be the most promising in recording interannual variability in SST structure. In particular, the NE monsoon period shows potential for providing information on regional climate and oceanography. The results suggest that, over the 20-year period of the records, relatively warm SST in the coastal Arabian Sea waters in the December to March NE monsoon season are usually followed by above-average rainfall during the summer SW monsoon in India. These positive SST anomalies could be a reflection of generally reduced wind speeds, using the logic that lower wind speed will result in less evaporative cooling of the sea surface, and a shallower surface ocean mixed layer and steep thermocline. Previous studies have identified weak positive SST anomalies in parts of the Arabian Sea in the 3–4 months prior to above-average rainfall Indian summer (SW) monsoons, followed by stronger negative SST anomalies during and in the few months following the rainy season (e.g., Shukla, 1987; Cadet and Diehl, 1984; Rao and Goswami, 1988).

Taken together, these observations indicate that weak NE monsoons are usually followed by strong SW monsoons, and conversely, strong NE monsoons are followed by weak SW monsoons. We are uncertain why this relationship should exist. However, the positive SST anomalies identified in our coral records match periods of warming in the Arabian Sea which Tourre and White (1995) identified as the early stages in the development of an Indian Ocean ENSO. This Indian Ocean ENSO-style phenomenon involves the evolution of positive SST anomalies in the Arabian Sea which propagate eastwards and equatorwards through time, to complete a cycle in approximately 3–4 years (since 1979). The gradual (i.e., interannual) evolution and migration of SST anomalies (positive and negative) through the Indian Ocean region will exert an influence on the atmospheric pressure fields which govern the Asian monsoon system. For example, during the onset phase of the Indian ocean ENSO, there are negative SST anomalies throughout much of the southern tropical Indian Ocean (at the same time as there are positive SST anomalies in the Arabian Sea). These below-average southern tropical SSTs may be responsible for reduced NE monsoon airflow over the Arabian Sea due to the direct effect of reduced temperature and pressure gradients between the southern tropical Indian Ocean and Himalayan/Tibetan Plateau region land mass and/or the indirect effect of convection changes on wind patterns. Under the same conditions, similar reasoning would lead to increased SW monsoon airflow. Therefore, we conclude that the apparent inverse relationship between NE and SW monsoon strengths may be a function of interannual evolution of the total Indian Ocean SST field.

Although the SW monsoon coral $\delta^{18}O$ records show no significant correlation with either COADS SST or Indian rainfall, the degree of correlation between the two coral records is as great for that season as it is for the NE monsoon season. Agreement between the coral $\delta^{18}O$ records indicates that coastal upwelling is faithfully recorded at these two sites. Detailed oceanographic and remote sensing studies of SW monsoon season upwelling in the region have identified extremely heterogeneous patterns of upwelling, including large- and small-scale eddies which evolve in space and time (Currie, 1992; Brock, McClain, Anderson et al., 1992). These result in steep thermal gradients across the sea surface. Therefore, the lack of correlation with other more regional climatic indices reflects the heterogeneous nature of SST along the Oman margin during the SW monsoon.

In summary, coral $\delta^{18}O$ data demonstrate the great potential of using large corals on the Oman coast for identifying both local and regional-scale climatic and oceanographic variability over the last 1–2 centuries. Of particular value may be the ability to examine the way in which relationships between spatially distant parts of the climate system evolve through time, i.e., the coral data may help assess variability in the strength of teleconnections which appear to be an important facet of the monsoon climate system. In turn, this may lead towards a better understanding of the causes of monsoon climatic variability.

CONCLUSIONS

Large, century old, colonies of massive *Porites* coral living in the coastal waters of southern Oman experience the effects of the seasonally reversing monsoon climate system. Cores from these colonies record aspects of past monsoon variability in the chemistry of the aragonite skeleton that is precipitated by the coral. We have examined the oxygen and carbon isotopic composition, barium content and the nature and occurrence of annual fluorescent bands with the objective of evaluating the potential of each tracer as a recorder of interannual variation in the monsoon climate system.

The Ba/Ca content of *Porites* coral skeletons from the Oman coast do not appear to show a simple response to the strength of SW monsoon upwelling. Extremely high concentrations of barium measured in the outer few years of growth, and the rapid decline of these concentrations towards more oceanographically plausible values down the cores, are interpreted as reflecting the incorporation of barium into the skeleton in some non-lattice bound phase which decays through time. Below the outer few years of growth, a strong seasonal cycle is present in the coralline barium signal, with highest concentrations approximately coinciding with the peak of SW monsoon SST cooling. Thus the corals do appear to document the seasonal upwelling of nutrient- and barium-rich waters to the sea surface. However, incomplete understanding of the processes of barium incorporation hinders the use of the coral-Ba results in reconstructing interannual variations in upwelling intensity in this particular setting.

The carbon isotopic composition of the coral skeletons display a strong annual cycle with a trend towards isotopically more negative values in the last 5–10 years of growth. However, with the possible exception of the aforementioned trend, the interannual variations in coral $\delta^{13}C$ appear to be controlled by local or colony-specific factors. Fluorescent banding in the skeletons of the *Porites* corals is annual, with the most brightly fluorescent skeleton being deposited in the months following the end of the SW monsoon upwelling season. The timing of the banding, combined with the apparent lack of any terrestrial organic source for the fluorophores, leads us to speculate that the fluorescence in these corals may derive mainly from the deposition or breakdown of marine organic matter.

The oxygen isotopic composition of the Oman corals demonstrates the most potential as an accurate recorder of variability in the monsoon climate system. Seasonal and interannual variations in coralline $\delta^{18}O$ primarily reflect SST variations. Interannual variations in coastal SST (as recorded by coral $\delta^{18}O$) are about double the magnitude of similar changes documented by nearby COADS SST data (coastal up to 100 km offshore). This difference between coral data and offshore SST records suggests that Oman coastal waters are particularly sensitive to interannual variability in monsoon circulation. Both of our coral records, as well as the COADS record, display trends towards increasing NE monsoon season SST through the period 1973–1991. In the coral records, the $\delta^{18}O$ trends are equivalent to about 0.5° C/decade.

During the SW monsoon period, steep spatial and temporal gradients in SST associated with the physical dynamics of upwelling are the most probable reasons for a lack of correlation of interannual variability in coral $\delta^{18}O$ records with either COADS SST or Indian rainfall. However, strong similarities in interannual variability between the two coral records suggests that corals could provide a useful record of past variations in the intensity of coastal upwelling in southern Oman.

The more uniform oceanographic conditions which prevail during the NE monsoon period lead to coralline $\delta^{18}O$ providing a robust record of interannual variations in regional SST. In addition, the coral $\delta^{18}O$ records show an excellent correlation with interannual variations in Indian rainfall. Positive coral-inferred SST anomalies in the Arabian Sea during the NE monsoon (interpreted as weak NE monsoon winds) appear to precede strong SW monsoons (positive rainfall anomaly in India). The coral-inferred SST anomalies for this season also appear to be a manifestation of a recently recognised Indian Ocean ENSO. These results suggest that analysis of corals from Southern Oman holds great potential for increasing our understanding of interannual climate variability and the operation of the Asian monsoon.

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APPENDIX

Stations used in construction of our Indian rainfall anomaly index.

World Meteorological Office Station number	Station name
425870	Daltonganj
426470	Ahmadabad
426710	Sagar
427540	Indore
428670	Nagpur Sonegaon
429090	Veraval
429330	Akola
430410	Jagdalpur
430570	Bombay/Colaba
430630	Poona
431280	Hyderabad Airport
431490	Vishakhapatnam
431850	Machilipatnam
431920	Goa/Panjim
431980	Belgaum/Sambra