

## ***Chapter 2. Coral Reef Records of Past Climatic Change***

**C. Mark Eakin<sup>1</sup> and Andréa Grottoli<sup>2</sup>**

<sup>1</sup>NOAA Coral Reef Watch, <sup>2</sup>Ohio State University

### **Abstract**

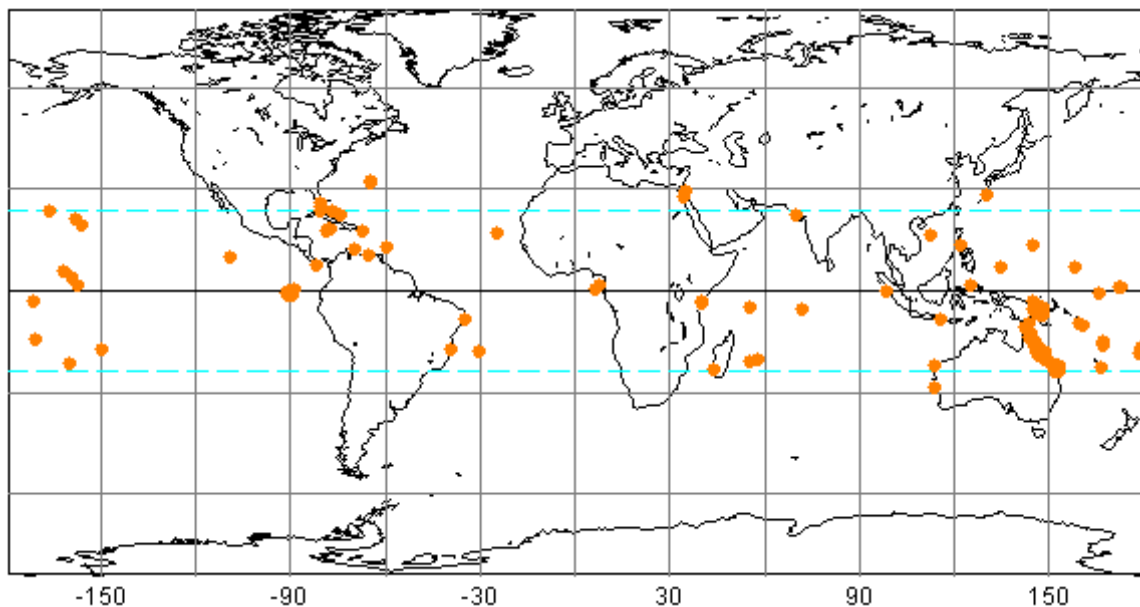
Coral skeletons serve as excellent natural archives of paleoenvironmental conditions in tropical and subtropical waters. The isotopic, trace, and minor elemental composition of coral skeletons can vary with environmental conditions such as temperature, salinity, cloud cover, river discharge, upwelling, and ocean circulation. As such, coral cores offer a suite of proxy records with the potential for reconstructing paleoclimatic and paleoceanographic conditions on interannual-to-centennial timescales. Living colonies can provide several centuries of continuous paleo-recordings and have been combined with fossil corals to reveal conditions over recent millennia and earlier periods. This chapter provides an overview of reconstructing environmental parameters from coral cores and some of the limitations of the various techniques. Corals have proven their worth as reliable recorders of past environmental conditions, but limitations exist due to the way that coral paleoclimatic records are collected and analyzed.

### **A Brief History of Coral Paleoclimatology**

Coral skeletons serve as excellent natural archives of paleoenvironmental conditions in tropical and subtropical waters. Living colonies can provide several centuries of continuous paleo-recordings and have been combined with fossil corals to reveal conditions over recent millennia and earlier periods.

The early 1970s, scientists discovered that corals regularly alternated the density of their calcium carbonate skeletons between seasons. With this discovery, sclerochronology (record of coral skeleton growth) was developed as an indicator of environmental conditions (Barnes 1973; Buddemeier et al. 1974; Knutson et al. 1972; Weber et al. 1975). In one of the first applications of this new tool, Hudson et al. (1976) made the connection to climate, or at least weather, by identifying stress bands recorded in corals during a cold winter in Florida in 1969-70. At about the same time, Weber and Woodhead (1972) applied geochemical analyses that had been in use in paleoceanographic studies to coral skeletons. Fairbanks and Dodge (1979) combined this with sclerochronology and found regular periodicity in geochemical ratios of  $^{18}\text{O}/^{16}\text{O}$  ( $\delta^{18}\text{O}$ ) of corals from Jamaica, Barbados, and Bermuda, with warm waters and high density skeletal bands corresponding to skeletons depleted in  $^{18}\text{O}$ . While ratios of

$^{13}\text{C}/^{12}\text{C}$  ( $\delta^{13}\text{C}$ ) were positively correlated at two sites, they were inversely correlated at the third – perhaps the first signal that  $\delta^{13}\text{C}$  variability was not driven by temperature but by some other environmental and/or biological parameter. Although sclerochronology continues to have direct applications as a temperature proxy (Lough and Barnes 1997; Slowey and Crowley 1995), most paleoclimatic data from corals now use geochemical analysis of their skeletons. More recently, sclerosponges have been investigated as paleoenvironmental recorders of both the surface and intermediate ocean waters. To date, approximately 100 coral skeletal and several sclerosponge isotopic and/or elemental records of 20 years or longer have been produced, most of which are available from the World Data Center for Paleoclimatology and other sources (Figure 1).



**Fig 1:** Locations of coral and sclerosponge records archived in the World Data Center for Paleoclimatology (<http://www.ncdc.noaa.gov/paleo/corals.html>) as of 1 June 2006.

## ***Introduction, Collection, Preparation, and Chronology Establishment***

### *Corals*

In the tropical oceans, the isotopic, trace and minor elemental composition of coral skeletons can vary as a result of environmental conditions such as temperature, salinity, cloud cover, river discharge, upwelling, and ocean circulation. As such, coral cores offer a suite of proxy records with potential for reconstructing tropical paleoclimatic and paleoceanographic conditions on interannual-to-centennial timescales. Massive, symbiotic stony corals are good tropical climate proxy recorders because: 1) they are widely distributed throughout the tropics, 2) their continuous annual skeletal banding pattern offers excellent chronological control, 3) they incorporate a variety of climate tracers from which paleo-ocean temperature, salinity, cloud cover, upwelling, ocean circulation, ocean mixing patterns, and other climatic and oceanic features can be reconstructed, 4) their proxy records can nearly match instrumental records for fidelity, 5) their records can span several centuries, and 6) their high skeletal growth rate (usually ranging from 5 - 25 mm /year) permits sub-seasonal sampling resolution. Thus proxy records in corals provide the best means of obtaining long seasonal-to-centennial timescale paleoclimatic information in the tropics.

When used in large numbers, like tree-ring site chronologies, growth records can be used as proxies for changing climatic conditions (Lough and Barnes 1997). In groups or individually, skeletal growth, or sclerochronology, provides information on environmental stress with corals growing faster in years of favorable conditions and more slowly under stressful conditions (Hudson et al. 1989; Eakin et al. 1994).

Geochemical records preserved in the coral skeleton are most commonly used to reconstruct paleotemperature records, but are also commonly used to reconstruct salinity, winds and upwelling, runoff, pollutants, and ocean mixing (Table 1 and following sections). In addition, the tropical habitat of corals and tropical origin of the El Niño-Southern Oscillation (ENSO) System has resulted in a natural pairing of corals as a source of proxy data on pre-instrumental ENSO variability. This continues to be an

important area of study, as ENSO clearly dominates interannual- to decadal-scale climatic variability (Quadrelli and Wallace 2004).

Not only do corals serve as proxies for modern climate, they have also been used to reconstruct conditions in the Holocene, Last Glacial Maximum, and last Interglacial. However, calibration issues typically prevent the geochemical proxies from being used to directly reconstruct temperatures, so these records are primarily used as relative indicators of temperature or other climatic variability. With living corals, the geochemical proxies can be compared with instrumental and remotely sensed temperatures, allowing calibration with varied levels of precision.

Table 1: Environmental variable(s) that can be reconstructed from coral skeletal isotopes, trace and minor elements, and growth records.

Proxy	Environmental variable
<b>Isotopes</b>	
$\delta^{18}\text{O}$	Sea surface temperature, sea surface salinity
$\delta^{13}\text{C}$	Light (e.g. seasonal cloud cover), plankton intake
$\Delta^{14}\text{C}$	Ocean ventilation, water mass circulation
$\delta^{11}\text{B}$	pH
<b>Trace and Minor Elements</b>	
Sr/Ca	Sea surface temperature
U/Ca	Sea surface temperature
Mg/Ca	Sea surface temperature
Mn/Ca	Wind anomalies, upwelling
Cd/Ca	Upwelling, contamination
Ba/Ca	Upwelling, river outflow
Pb/Ca	Gasoline burning
<b>Skeleton</b>	
Skeletal growth bands	Light (seasonal changes), stress, water motion, sedimentation, sea surface temperature
Luminescence	River outflow, ocean productivity

*Method:* Massive stony corals of the genera *Porites*, *Pavona*, and *Montastraea* are most commonly targeted for paleoclimatic studies because they form large mounding colonies with distinct annual bands, can grow for several hundred years, and are common. Continuous records of past tropical climate conditions are obtained by extracting a core from an individual massive coral head along its major axis of growth. Typically, this involves drilling a corer through the top center of the coral head to its initial point of growth (Figure 2). The extracted core is cut longitudinally into slabs ranging in thickness from 0.5 - 1 cm, cleaned with water and dried, then X-rayed. X-ray positive prints reveal the banding pattern of the slab and are used: 1) as a guide for sample drilling and 2) to establish a chronology for the entire coral record when the banding pattern is clear. In some cases, the x-rays serve as environmental proxies in and of themselves (see *Coral Growth as an Indicator of Environmental Stress*). In a few cases, composite records have been made by using multiple cores to extend the record length beyond that available from a single core (Cobb et al. 2003; Dunbar et al. 1994).

For geochemical analysis, carbonate powder samples are extracted along the major axis of growth by grinding the skeletal material with a dental drill bit. For high-resolution paleo-reconstructions, samples are extracted every millimeter or less along the entire length of the core. Since corals grow about 5 - 15 mm per year, this sampling method can yield sub-seasonal resolution. Much higher resolution sampling is possible by microdrilling or using laser ablation techniques that yield samples at approximately weekly temporal resolution (Sinclair et al. 1998), but this is not commonly performed. The coral carbonate powder is then analyzed for one or more isotopes or elements to build any one of a number of possible paleo-proxy records (Table 1). In most cases, the stable oxygen ( $\delta^{18}\text{O}$ ) and carbon ( $\delta^{13}\text{C}$ ) values of each sample are measured. Since the  $\delta^{13}\text{C}$  and/or  $\delta^{18}\text{O}$  composition of corals usually have a strong seasonal component, they are often used to establish the chronology in the absence of banding, and/or to confirm or adjust the chronology established from skeletal bands.

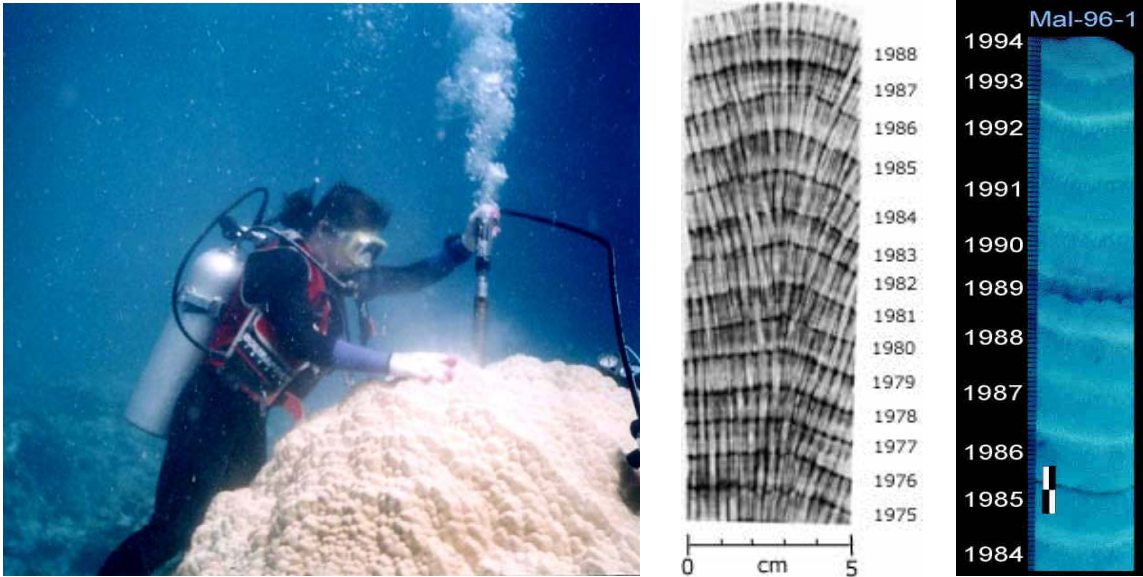


Fig 2: Illustration of coral cores and their extraction. From left to right: *Porites lutea* being cored by one of the authors (AGG) in Saipan (July 2003), x-radiograph of a *Montastraea* coral core from Florida (Halley et al. 1994), and an image of coral luminescence in a *Porites lutea* core from Kenya (unpublished image of record from Cole et al. 2000).

### *Sclerosponges*

Sclerosponges are slow growing calcareous sponges that are normally found in protected, shaded microhabitats on reefs and walls, ranging from sub-surface to 1000m depths, and can often be found exposed to open oceanic waters. Their growth rates range from 0.1 – 1.6 mm / year and can grow for up to 1000 years (Benavides and Druffel 1986; Böhm et al. 1996, 2002; Fallon et al 2003; Grottoli unpublished; Hughes and Thayer 2001; Reitner et al. 1996; Swart et al. 1998, 2002; Willenz and Hartmen 1985; Wörheide et al. 1997). Published growth rates for *Acanthocheatetes wellsi*, *Astroclera willeyana*, and *Ceratoporella nicholsoni* are 0.05-1.6, 0.35 – 1.6, and 0.1-0.4 mm/year, respectively. Sclerosponges are emerging as good paleoclimatic recorders and complement the information provided by faster growing corals (Swart et al. 1998a). The slower growth often limits sclerosponge resolution (but see exception to this in Grottoli in press) but

allows many sclerosponges to record several centuries of information. They are found throughout the tropics across a wide depth range (surface to 1000m) and can live for several centuries. In addition, sclerosponges appear to accrete their calcium carbonate skeleton in isotopic equilibrium with seawater due to the absence of photosynthesis and relatively low metabolic activity, thus more directly recording oceanic chemistry than corals ( $\delta^{18}\text{O}$ : Moore et al. 2000;  $\delta^{13}\text{C}$ : Böhm et al. 1996; Druffel and Benavides 1986; Wörheide et al. 1997). As such, sclerosponges appear to be reliable proxy recorders of seawater dissolved inorganic carbon  $\delta^{13}\text{C}$  (DI- $\delta^{13}\text{C}$ ) (i.e., Druffel and Benavides 1986) and seawater  $\delta^{18}\text{O}$  ( $\delta^{18}\text{O}_{\text{sw}}$ ) (Swart et al 2002). Recent work suggests that the ratio of strontium to calcium (Sr/Ca) in sclerosponges may be a proxy for ocean temperature (Haase-Schramm et al. 2003; Swart et al. 2002; Rosenheim et al. 2005). Because sclerosponges are not light limited with no detectable metabolic fractionation effects on isotopic or elemental signatures, sclerosponge-derived proxy records can lend great insights into the regional and temporal variability of oceanographic features such as thermocline depth, upwelling, ocean ventilation, and the uptake rate of anthropogenic carbon from the atmosphere into the oceans. This provides an improved knowledge of the spatial and temporal variability in surface and depth integrated DI- $\delta^{13}\text{C}$  inventory changes that extends the well-used WOCE data set hundreds of years in the past for tropical reef locations.

*Method:* Sclerosponges of the *Ceratoporella* (Caribbean), *Acanthocheatetes* (Pacific), and *Astroclera* (Pacific) genera are the most commonly used for paleoclimatic reconstruction. The specimens are typically collected across a depth range of 1-300 m using either SCUBA or submersible vehicles. A sclerosponge specimen is then cut in half or into slabs along its major axis of growth. X-rays are typically not very informative in sclerosponges as their banding is not annual. However, by using a combination of x-rays and following skeletal microstructure, the sclerosponge slab is sampled by milling the skeleton along the maximum axis of growth at 0.1 mm increments or less using a high-precision microdrill down the length of the slab (Grottoli in press; Hughes and Thayer 2001; Swart et al. 2002). The sclerosponge carbonate powder samples are then analyzed for one or more isotopes or elements to build

paleoceanographic records. The chronology is established by using a combination of radiogenic dating, stable isotope records, and estimated growth rates. The bomb-radiocarbon signature ( $\Delta^{14}\text{C}$ ) introduced into the skeleton from atmospheric bomb testing (1955-1963) is used to help anchor the chronology. In some cases, the ratio of Uranium to Thorium (U/Th) is also used to date the pre-bomb sections of sclerosponge records. Since exact annual dating is not possible in sclerosponges, paleo-reconstructions from these records tend to focus on decadal-to-centennial timescale processes. Similar to corals, other geochemical proxies may also be analyzed.

### ***Coral Paleotemperature and Salinity***

The  $\delta^{18}\text{O}$  and Sr/Ca signatures in corals have proven to be very reliable paleotemperature proxies (Druffel 1997; Gagan et al. 2000; Grottoli 2001). Since large corals suitable for paleoclimatic reconstructions are typically limited to the top ~20m of the ocean, their proxy records reflect near-surface ocean conditions found on coral reefs.  $\delta^{18}\text{O}$  has the longest history as a temperature proxy and, up until recently, was more common and less expensive than elemental measurements. Unfortunately, coral skeletal  $\delta^{18}\text{O}$  is influenced by both temperature and salinity, and is therefore not a pure indicator of temperature. This confounding influence is minimized when the relative contribution from either salinity or temperature variability is low or the two variables combine to increase the change in coral  $\delta^{18}\text{O}$  (Felis et al. 2000; Le Bec et al. 2000; Swart et al. 1998b). Fortunately, recent improvements in instrumentation have made the application of strontium to calcium (Sr/Ca) in coral skeletons practical as a coral paleothermometer (Beck et al. 1992). Sr/Ca ratios are not influenced by salinity, making it a direct paleothermometer with few sources of outside noise. This also provides the possibility of detecting salinity changes through the difference between these two geochemical tracers (Gagan et al. 1998; Linsley et al. 2004; McCulloch et al. 1994; Quinn and Sampson 2002; Ren 2002; Swart et al. 1999). A few individuals have applied two other paleothermometers: uranium to calcium (U/Ca) and magnesium to calcium (Mg/Ca) ratios. U/Ca ratios may provide the same level of accuracy or precision of temperature

reconstructions as Sr/Ca, but this is still being confirmed (Corrège, et al. 2000; Hendy et al 2002; Min et al. 1995; Shen and Dunbar 1995). Mg/Ca (Mitsuguchi et al. 1996) ratios are probably not accurate enough to replace other proxies (Meibom 2004; Schrag 1999). While each of these has value alone, the greatest strength may lie in a multiproxy approach. Solow and Huppert (2004) recently proposed a technique that may improve the error by combining several elemental paleothermometers. Finally, while coral skeletal  $\delta^{18}\text{O}$  has a direct value as a paleothermometer, it also can provide information on upwelling (i.e., Guilderson and Schrag 1989b).

#### *Stable Isotope Analyses ( $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ )*

Skeletal  $\delta^{18}\text{O}$  in marine organisms is affected by temperature-induced fractionation and  $\delta^{18}\text{O}$  of the surrounding water (Epstein et al. 1953). As temperature increases, the  $^{18}\text{O}$  fraction of the coral skeleton decreases (Kim and O'Neil 1997). Based on empirical studies, a  $1^\circ\text{C}$  increase in water temperature corresponds to an average decrease of about 0.22‰ in coral  $\delta^{18}\text{O}$  though that slope can vary significantly from 0.15 to 0.24‰ among species and locations (i.e., Linsley et al. 1999; Wellington and Dunbar 1995; Wellington et al. 1996). The  $\delta^{18}\text{O}$  in seawater and coral skeletons also decreases as salinity decreases, because precipitation is depleted in  $\delta^{18}\text{O}$  relative to seawater, especially in tropical environments where greater convection of moisture reduces the  $^{18}\text{O}$  in cloud-borne moisture. In both corals and sclerosponges, the interpretation of the skeletal  $\delta^{18}\text{O}$  record depends on the hydrological regime of the collection site. While not a paleothermometer, skeletal  $\delta^{13}\text{C}$  in corals is typically analyzed along with  $\delta^{18}\text{O}$  (see discussion in *Cloud Cover and Feeding*).

*Method:* Carbonate powder samples are analyzed for  $\delta^{18}\text{O}$  (the per mil deviation of the ratio of  $^{18}\text{O}/^{16}\text{O}$  relative to the Peedee Belemnite (VPDB) Limestone Standard) and  $\delta^{13}\text{C}$  (ratio of  $^{13}\text{C}/^{12}\text{C}$  relative to PDB) by acidifying the sample in 100% ortho-phosphoric acid and measuring the resulting  $\text{CO}_2$  with a mass spectrometer. Automated common acid bath or carbonate Kiel devices are commonly used, especially for small samples.

Typically, 10% of samples are run in duplicate to ensure reproducibility and the accepted precision of replicate analyses is now  $\leq 0.05\%$  for  $\delta^{13}\text{C}$  and  $\leq 0.09\%$  for  $\delta^{18}\text{O}$ . Today, as little as ~80 - 150  $\mu\text{g}$  of sample material is now used for stable isotope analyses.

### *Strontium to Calcium and Uranium to Calcium*

Strontium and uranium have long residence times in seawater. Because this provides relatively constant concentrations in surface seawater, the observed fluctuation in coral Sr/Ca has been attributed to changes in SST (Weber 1973). The application of U/Ca is more recent, but shows promise (Corrège, et al. 2000; Hendy et al 2002; Min et al. 1995; Shen and Dunbar 1995). Sr and U replace Ca in the skeletal aragonite through thermodynamic processes, with less replacement of Ca by the heavier elements at higher temperatures (Beck et al. 1992; Weber 1973). Although it is a well-established geothermometer, SST-Sr/Ca calibration curves often vary dramatically among species and/or locations, and may be influenced by growth rate (e.g.: Beck et al. 1992; Boiseau et al. 1997; deVilliers et al. 1995; Gagan et al. 2000; Goodkin et al. 2005; Marshall and McCulloch 2002). Thus Sr/Ca needs to be calibrated to local or regional temperature records for each genus or species and at every location.

*Method:* Carbonate powder samples are dissolved in acid and the Sr/Ca or U/Ca ratio in the solution is measured using a variety of techniques. TIMS (thermal ionization mass spectrometry), ICP-MS (inductively coupled plasma mass spectrometry), and ICP-OES (inductively coupled plasma optical emission spectroscopy) are some of the tools used to measure Sr/Ca and U/Ca values in carbonates. In most cases, small samples (100 – 1000  $\mu\text{g}$ ) are used for each analysis. The currently accepted precision for Sr/Ca analyses of duplicate corals or sclerosponge samples is  $\pm 0.02\%$  ( $1\sigma$ ).

### *Other Applications of Coral Proxy Paleodata*

In addition to providing proxy records of paleo-sea surface temperature, coral records have been used to reconstruct paleo-circulation, -salinity, -pH, -runoff, -cloud cover, and -nutrients from both modern and fossil corals.

#### *Cloud Cover and Feeding ( $\delta^{13}\text{C}$ )*

While less commonly reported than  $\delta^{18}\text{O}$ , most researchers collect data on  $\delta^{13}\text{C}$  at the same time as  $\delta^{18}\text{O}$ . Photosynthesis (light) and feeding (which directly affects the respired  $\delta^{13}\text{C}$ ) are the primary influences on coral skeletal  $\delta^{13}\text{C}$ . For corals collected from shallow, non-upwelling sites where coral feeding is relatively constant, changes in  $\delta^{13}\text{C}$  are predominantly driven by changes in photosynthesis, providing a record of seasonal changes in cloud cover or turbidity (i.e., rainy season vs. dry season) (Cole et al 1990; Grottoli 1999, 2002; Grottoli and Wellington 1999; McConnaughey 1989a, b). In addition, because of the loss of algal symbiotes during bleaching, decreases in photosynthesis and/or changes in feeding may be recorded in the skeleton of bleached corals (Grottoli et al. 2004). In upwelling regions where feeding opportunities can vary dramatically, changes in  $\delta^{13}\text{C}$  have been used as an indicator of vertical mixing through change in coral food source (Felis et al. 1998) and in DI- $\delta^{13}\text{C}$  (Abram et al. 2003). In the latter case, a dramatic change in DI- $\delta^{13}\text{C}$  off Indonesia, attributed to iron fertilization from the 1997 forest fires, resulted from unprecedented blooms of red tide algae. These elevated levels of primary production caused a shift in the seawater DI- $\delta^{13}\text{C}$  that was recorded in coral skeletons. Unlike corals, sclerosponges appear to deposit their skeleton in isotopic equilibrium with seawater and records the  $\delta^{13}\text{C}$  of the surrounding DI- $\delta^{13}\text{C}$  (see anthropogenic carbon input section below for details).

#### *Ocean circulation: Radiocarbon Analyses ( $\Delta^{14}\text{C}$ )*

$^{14}\text{C}$  is produced naturally in the stratosphere and was also produced as a result of thermonuclear weapons explosions in the atmosphere in the 1950s and early 1960s. The base of the  $\Delta^{14}\text{C}$  -bomb is clearly identifiable as ~1955 in coral and sclerosponge carbonate records (i.e., Druffel 1981; Druffel and Linick 1978; Fallon et al 2003). During the pre-bomb period, coral  $\Delta^{14}\text{C}$  records reflect a declining trend in the 20<sup>th</sup> century termed the Suess Effect: the decrease in  $^{14}\text{C}$  in the atmosphere due to dilution of natural

$^{14}\text{C}$  by the addition of  $^{14}\text{C}$ -free fossil fuel  $\text{CO}_2$  (i.e., Druffel and Griffin 1993, 1999; Druffel et al. 2001). Post-1955, the bomb-curve signal can be used to help confirm/establish coral and sclerosponge chronologies. As a new proxy,  $\Delta^{14}\text{C}$  is an excellent tracer for detecting upwelling and changes in seawater circulation since deep water has a lower  $\Delta^{14}\text{C}$  value than surface water (i.e., Druffel and Griffin 1993; Fallon et al 2003; Grottoli et al 2003; Grumet et al 2004; Guilderson and Schrag 1998a). For example, in the eastern equatorial Pacific Ocean, increased upwelling or increases in the proportion of deep water transported to the surface results in a decrease in the  $\Delta^{14}\text{C}$  of the skeleton, making corals in these locations excellent recorders of upwelling and of changes in upwelling regimes.  $\Delta^{14}\text{C}$  evidence from the Galapagos indicates that there was a major shift in the source of upwelling water in 1976 when decadal-scale Pacific Ocean temperature variability Pacific Decadal Oscillation (PDO, Mantua et al. 1997) switched from a negative to a positive phase (Guilderson and Schrag 1998b). Work by Grottoli et al (2003) shows that a PDO switch from positive to negative in the late 1940s also appears to be associated with a major change in the source water upwelling in the central equatorial Pacific. At Rarotonga, a  $\Delta^{14}\text{C}$  seasonal variation of 10-15‰ indicates that vertical mixing occurs each year (Guilderson et al 2000). Combining coral  $\Delta^{14}\text{C}$  data from Rarotonga, Galapagos, and the Solomon Sea, Guilderson et al. (2004) constructed a mixing model that shows variations in the amount of eastern Pacific water entering the Solomon Sea both on El Niño and decadal timescales.

*Method:* Approximately 7-10 mg of coral or sclerosponge carbonate powder is acidified under vacuum to produce  $\text{CO}_2$  gas. For analysis by accelerator mass spectrometry (AMS), the  $\text{CO}_2$  is reduced with hydrogen gas on iron or cobalt metal catalyst to produce a graphite target that is analyzed by AMS (Vogel et al. 1987). For gas counting analyses, the  $\text{CO}_2$  is measured directly. In all cases, results are reported as  $\Delta^{14}\text{C}$  (the per mil deviation of  $^{14}\text{C}/^{12}\text{C}$  of the sample relative to that of 95% Oxalic Acid-1 standard) (Stuiver and Polach 1977). All  $\Delta^{14}\text{C}$  values are corrected for fractionation to a  $\delta^{13}\text{C}$  of -25‰.

#### *Anthropogenic Carbon Input Rates Into the Tropical Ocean*

Estimates of the uptake of CO<sub>2</sub> by the oceans and of the imbalance between air-sea CO<sub>2</sub> reservoirs contain a large degree of uncertainty that greatly influences our understanding of oceanic CO<sub>2</sub> uptake. This is largely attributed to a lack of instrumental data on seawater DI-δ<sup>13</sup>C and isotopic air-sea disequilibrium (Gruber and Keeling 2001; Heimann and Maier-Reimer 1996; Kortzinger et al. 2003; Quay et al. 1992; Quay et al. 2003; Tans et al. 1993). Local carbon inventory changes can be reliably estimated by monitoring the change in DI-δ<sup>13</sup>C but not as well by DI-Δ<sup>14</sup>C (Heimann and Maier-Reimer 1996; Kheshgi et al. 1999). An improved knowledge of DI-δ<sup>13</sup>C inventory changes over space and time would decrease the uncertainty in CO<sub>2</sub> uptake models (Gruber and Keeling 2001; Heimann and Maier-Reimer 1996; Quay et al. 1992, 2003; Sonnerup et al. 1999; Tans et al. 1993). In addition, the rate of DI-δ<sup>13</sup>C change prior to 1970 is unknown from instrumental data. Sclerosponges, are uniquely suited to filling these data gaps because they typically are exposed to open ocean conditions.

Though not yet directly calibrated, *Ceratoporella nicholsoni* (Jamaica) and *Acanthochaetetes wellsi* (New Caledonia) sclerosponges appear to precipitate their skeletal δ<sup>13</sup>C in isotopic equilibrium with the surrounding seawater (Böhm et al. 1996; 2002; Druffel and Benavides 1986; Fallon et al. 2003; Lazareth et al. 2000; Wörheide et al. 1997). These authors have found that the δ<sup>13</sup>C of sclerosponges growing within the mixed-layer has decreased with decreases in atmospheric δ<sup>13</sup>C<sub>CO2</sub> over the past few centuries (Suess Effect). In the Great Barrier Reef, Caribbean and New Caledonia, sclerosponge δ<sup>13</sup>C decreased by 0.5-1.0‰ from 1800-1990 with most of the decrease occurring in the latter part of the past century (Böhm et al. 1996, 2002; Druffel and Benavides 1986; Joachimski et al. 1995; Lazareth et al. 2000; Wörheide et al. 1997). Regional variability in the decreases in sclerosponge δ<sup>13</sup>C is indicative of differences in the proportional contribution of ocean-atmosphere CO<sub>2</sub> flux, mixed-layer depth, water mass mixing to the DI-δ<sup>13</sup>C at each site, as well as chronological accuracy. However, none of these published records are annually resolved nor directly calibrated with seawater DI-δ<sup>13</sup>C, thus limiting our ability to fully and quantitatively interpret or detect any sub-decadal variability in sclerosponge δ<sup>13</sup>C. Once calibrated, sclerosponges have the potential to fill at least part of that data gap by providing a significant archive of

quantitatively robust proxy  $\text{DI-}\delta^{13}\text{C}$  for the past centuries throughout the tropical Pacific and across depths of several hundred meters.

*Upwelling, Nutrients, and pH: Other Elemental Ratios and Analyses*

In addition to Sr/Ca and U/Ca ratios, other elemental ratios that are measured for paleoceanographic reconstructions include: cadmium to calcium (Cd/Ca), barium to Ca (Ba/Ca), manganese to Ca (Mn/Ca), and magnesium to Ca (Mg/Ca). Since the focus of this review is on the more commonly reported coral and sclerosponge paleo-records, we will only briefly cover these other elemental records here. A large suite of analytical techniques exists for measuring these elemental ratios including ARS-1 (graphite furnace atomic absorption), ICP-MS (inductively coupled plasma mass spectrometry), and LA-MS (laser ablation mass spectrometry). Ba/Ca, Mn/Ca and Cd/Ca have been used as upwelling and/or nutrient proxies (Fallon et al. 1999; Reuer et al 2003; Shen et al 1987, 1991, 1992a, b) and Ba/Ca records have recently been found to be excellent recorders of river discharge in corals growing in the flood plume of rivers. McCulloch et al. (2003) used barium records as a proxy for river sediment discharge in a 250-year long Great Barrier Reef *Porites* and found substantial increases in the sediment content of river floods in the period since European settlement of Australia. Abram et al. (2003) used peaks in Mn, lanthanum, and yttrium as indications of an extreme outbreak of red tide that resulted in coral and fish deaths in Indonesia.

Shen et al. (1987, 1992a) pioneered the idea of using Cd/Ca as a paleo-upwelling recorder. Cd concentrations are higher in the deep ocean than in the surface ocean where it is biodepleted, so Cd appears to be a better recorder of upwelling than Ba because Cd input from land is relatively low compared to Ba. Cd/Ca records from corals not only show the frequency of upwelling events, but their relative duration and relative intensity. Further calibration development of this proxy would greatly enhance our ability to quantify upwelling and compare Cd/Ca records among corals and among locations.

Ocean acidification has recently been identified as a major concern for corals and other calcifying organisms (Kleypas et al. 2006, Kleypas and Langdon this volume). A

new proxy with exciting possibilities is the use of Boron stable isotopes ( $\delta^{11}\text{B}$ ) as a proxy for pH. Gaillardet and Allègre (1995) first tested this proxy in corals, but it has not yet been widely applied. Most recently, Hönisch et al. (2004) performed the necessary laboratory and field experiments to calibrate this new proxy and Pelejero et al. (2005) published the first multicentury pH reconstruction from a coral.

### *Lead and Other Metal Contaminants*

Coral skeletons can trap particulate contaminants, providing a record of contaminant input into reefal waters through airborne or waterborne pathways. Early work by Dodge and Gilbert (1984) led to the application of this approach to reconstructing lead input into the atmosphere since 1850 (primarily from gasoline burning) using contamination of a long coral core from Bermuda and shorter cores from other locations around the globe (Shen and Boyle 1987). Detection of lead and other heavy metals has been used to measure changes in local- to regional-scale human activity and gasoline use at various locations, primarily as an indicator of airborne contamination (Desenfant et al. 2003; Medina-Elizalde et al. 2002; Reuer et al. 2003). Shen et al. 1987 also found that cadmium not only can be used as an indicator of upwelling, but also can be used as an indicator of airborne industrial pollutants. In a different application, Fallon et al. (2002), used lead in coral skeletons to detect lead and other contaminant elements entering the water directly from mining activity in Papua New Guinea. The concentration of lead in the ocean steadily increased from 1880-1979 due to the combustion of leaded-gasoline. This lead concentration peak is unambiguous and has been used to date sclerosponge records in the Caribbean (Swart et al 2002).

### *Runoff: Detection through Luminescent Banding*

Luminescent banding has been found in corals from many locations. Initially, Isdale (1984) reported that fluorescent bands in coral skeletons were an indicator of flow from the Burdekin River. Many researchers began to apply this elsewhere, finding luminescence from non-riverine sources (Theodorou 1995; Tudhope et al. 1996) and discovering that both fluorescent and phosphorescent compounds contribute to the signal

(Wild et al. 2000). Isdale et al. (1998) were able to reconstruct 83% of the annual (water year) variability of Burdekin River flow using two long coral records, and Lough et al. (2002) have found high correlations between several rivers in northeastern Australia and luminescence in nearshore corals along the Great Barrier Reef. Coral luminescence has been applied to precipitation and related variables in the Red Sea (Klein et al. 1990), the Arabian Sea (Tudhope et al. 1996), the Caribbean (Nyberg 2002), Florida (Smith et al. 1989), the South China Sea (Peng et al. 2002), and Papua New Guinea (Scoffin et al. 1989; Tudhope et al. 1995).

While Isdale identified the fluorescent bands as humic and fulvic compounds resulting from decaying land plants, this has been debated by other authors. Additionally, it was quite some time before this proxy was successfully applied to other locations. It appears that coral fluorescence only captures river flow under a narrow range of input rates, making it a very useful proxy, but only at a limited number of sites. Non-riverine sources may also produce luminescent bands in corals. Tudhope et al. (1996) found luminescence in corals from arid Arabian Sea corals, concluding that the bands were related to the breakdown of highly seasonal plankton blooms.

#### *Coral Growth as an Indicator of Environmental Stress*

While geochemical records are more frequently used for climatic reconstruction, coral growth continues to be used to detect broadly defined stress events. This usually involves the use of multiple cores from multiple colonies (Lough and Barnes 1997). However, single long records can prove useful in particular environments. The latter was the case of a centuries-long record of wind-induced mixing from Bermuda (Pätzold et al. 1999). More generalized stress has been detected through analysis of coral growth, applying sclerochronology to indicate clear changes in corals' responses to parameters such as sediments, nutrients, temperature, and salinity. Hudson pioneered the use of coral growth bands as an indicator of environmental perturbations in the Florida Keys, finding distinct stress bands and multi-year growth reductions related to natural events such as cold winters and hurricanes and human events such as dredge and fill activities and railroad construction (Hudson 1981; Hudson et al. 1976, 1989). Dodge and Lang (1983)

applied dendrochronological (tree-ring) methods to corals from the East Flower Gardens Bank and found both anticipated annual signals and also decreased growth in years with high discharge from the nearby Atchafalaya river.

These studies led to further use of stress banding as an indicator of disturbance. Eakin et al. (1994) measured the growth rate of a series of corals collected along the southeastern coast of Aruba both upstream and downstream of a major coastal oil refinery. They were able to relate clear changes in growth of the nearby and downstream corals with major changes in refinery operations, probably mostly an impact from sedimentation. However, increased sedimentation does not always result in reduced coral growth. Barnes and Lough (1999) found a decrease in coral growth in Papua New Guinea corals near a gold mine, but there was no relationship between growth and distance from the mine. They concluded that growth decreases resulted from regional changes and were not related to mine-based sediments. Eakin et al. (1993) looked at stress bands and growth rates in Persian Gulf corals and found evidence of stress during the 1991 Gulf War and the Iraqi burning of Kuwaiti oil fields. Coral bleaching also is suspected of reducing coral growth resulting in stress bands (Abram et al. 2003; Leder et al 1991; also see Future Applications).

### *Fossil Corals*

Recently, the use of fossil corals has provided windows into periods when past climates were either different from today or when similar conditions occurred in the distant past. Most prominently, these include snapshots of climatic variability in the Holocene and Younger Dryas (Beck 1997; Corrège et al. 2004; Felis et al. 2004; Gagan et al. 2004; McCulloch et al. 1996; Moustafa et al. 2000; Tudhope et al. 2001; Woodroffe and Gagan 2000; Woodroffe et al. 2003; Yu et al. 2004;), the last glacial maximum (Gagan et al. 2004; Tudhope et al. 2001), or the last interglacial (Felis et al. 2004; McCulloch et al. 1999; McCulloch and Esat 2000; Tudhope et al. 2001). These have provided important, seasonally resolved insights into how the climate system operated during those periods. Unfortunately, they only provide windows of variability and are neither exactly dated (i.e., chronology is typically anchored within +/- 50 years), nor do

they provide records continuous to modern times. In one case, work is progressing on a long, continuous coral proxy record of the last millennium. Cobb et al. (2003) spliced together fossil coral materials to develop a series of overlapping records for Palmyra Island, with the eventual hope to develop a continuous, millennial-scale, annually resolved tropical record. We hope other researchers will seek out additional locations where this approach may be applied.

### *Climatic Data for Retrospective Monitoring*

Despite the value of coral skeletons as recorders of past climate and environmental stress, most funding and research have focused on reconstructing large-scale climate patterns. They typically have not been considered as necessary parts of monitoring programs. As a result, of over 200 coral paleoclimatic data sets in the holdings of the World Data Center for Paleoclimatology (<http://www.ncdc.noaa.gov/paleo/corals.html>) on 1 June 2006, only 10 were from areas of U.S. management interest. Fortunately, the U.S. National Oceanic and Atmospheric Administration (NOAA) recently developed an integrated program of monitoring coral reefs. The Coral Reef Watch (Liu 2006; Strong et al. 2002, this volume; <http://coralreefwatch.noaa.gov/>) includes a wide range of observations on coral reefs including the use of coral paleoclimatic data to provide “retrospective” monitoring of reefs before monitoring was implemented (Eakin et al. in press). Paleoclimatic records need to be included in monitoring programs in the future so that marine protected area management can benefit from paleo records.

### *Gaps and Challenges for the Future*

While corals have proven their worth as reliable recorders of past environmental conditions, limitations exist due to the way that coral paleoclimatic records are frequently collected and analyzed. In general, laboratory precision is no longer a major issue (Lough 2004). The important limiting factors now tend to be the frequent use of single

cores for analysis (Lough 2004) and insufficient temporal resolution (Felis and Pätzold 2004). This is due to the potentially large range in isotopic (Grottoli 1999, 2000, 2001) and Sr/Ca natural variability among coral heads, locations, species, and depth. Among-colony natural variability in other trace elements has not been investigated, but is likely to be important as well. It cannot be stated too strongly: multiple colonies need to be cored to help identify local perturbations that limit the reliability of geochemical proxies as recorders of climate. Ideally, this should involve multiple records from each of multiple (at least 3) colonies (Lough 2004). Additionally, much more information is available when records are analyzed at sub-seasonal resolutions. Felis and Pätzold (2004) discuss particular value of bimonthly resolution, which is probably the best balance between resolution and cost. While in some cases multiple old colonies are not available, both under replication and insufficient temporal resolution are frequently the result of budgetary restraints placed on the projects. Funding organizations need to realize that while paleo reconstructions from corals are quite cost-effective, they must be funded at levels that provide reliable records.

We can now unravel temperature and salinity from coral geochemical records with high fidelity. Still unsolved, however, is the ability to identify past bleaching events in coral geochemical or skeletal growth records. While we can determine levels of stress that we believe should be sufficient to cause bleaching, we cannot yet identify when an individual coral bleached. Such an ability would provide a tremendous increase in the information we can glean from corals relative to both their past history of bleaching, and the relationship between bleaching and natural climatic variability.

Some studies have addressed this question and yielded clues to possible markers. Leder et al. (1991) found distinct skeletal and isotopic signatures to bleaching events in *Montastraea annularis* from Florida. Most importantly, this study and a subsequent one using *Porites lutea* in Thailand (Allison et al. 1996) revealed that reduced calcification at the time of bleaching may limit the ability of bleached corals to record high temperature excursions. Both of these studies, and subsequent work from Australia and Japan (Suzuki et al. 2003) and Hawaii (Grottoli et al. 2004), revealed visible changes in  $\delta^{13}\text{C}$  that

probably were related to metabolic and dietary changes during and subsequent to bleaching. These studies indicate that skeletal stress bands,  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  changes may provide clues to past bleaching. However, all of these records are sufficiently variable that the solution to the problem is still unresolved.

More recent work on branching *Porites divericata* has revealed a shift in the ratio of certain trace metals in the skeleton of bleached colonies (Burr 2002). Burr found statistically significant differences in amounts of strontium, selenium and silver from bleached and unbleached *P. divericata*. Changes in selenium and silver may provide useful bleaching indicators that are independent of the  $\delta^{18}\text{O}$  and Sr/Ca paleothermometers, but the work also raises some concern that Sr/Ca ratios may be modified through bleaching. Burr also found that the skeletal microstructure of the bleached corals has a “melted” appearance similar to that seen in bleached foraminifera (Toler and Hallock 1998). Such malformations may be related to the reduced calcification seen after bleaching and may provide distinct bleaching clues.

The concern over lost growth bands (per Leder et al. 1991) has prompted Halley and Hudson (pers. comm.) to compare luminescence bands to growth bands to try to identify loss of bands due to bleaching. Their preliminary work indicates no loss of bands between 1878 and 1986 in cores from Biscayne National Park, Florida, indicating that bleaching is strictly a recent phenomenon at those sites.

### ***Conclusions***

The use of coral skeletons as recorders of paleoenvironmental information has come a long way in the thirty years since its inception. They continue to be used as proxies of past climate, especially large scale climate such as ENSO and the North Atlantic Oscillation. The use of corals as environmental monitors both as part of comprehensive programs and for detecting land-based stress is increasing, as are many other uses of coral paleodata. The use of sclerosponges is just gaining popularity, but work so far suggests that it will also become a valuable source of paleoclimatic

information. Despite the use of these proxies so far, there are still many new areas that need to be explored and new applications left to be discovered.

### ***Acknowledgements***

We thank the many authors who have contributed their data to the World Data Center for Paleoclimatology in Boulder, CO. Without their participation in data sharing, this and many other publications would not be possible. We thank the NOAA/MASC Library for helping us find copies of publications. CME also thanks Wendy Gross for providing figures and other support. AG also thanks the Woodrow Wilson Foundation Early Career Fellowship grant, NSF grant #OCE-0426022, and the Mellon Foundation grant #1040644.

### ***Literature Cited***

Abram, N J., M. K. Gagan, M. T. McCulloch, J. Chappell, and W. S. Hantoro, Coral reef death during the 1997 Indian Ocean Dipole linked to Indonesian wildfires, *Science*, 301, 952-955, 2003.

Allison, N., A. W. Tudhope, and A. E. Fallick, Factors influencing the stable carbon and oxygen isotopic composition of *Porites lutea* coral skeletons from Phuket, South Thailand, *Coral Reefs*, 15, 43-57, 1996.

Barnes, D. J., Growth in colonial scleractinians, *Bulletin of Marine Science*, 23, 280-298, 1973.

Barnes, D. J., and J. M. Lough, *Porites* growth characteristics in a changed environment: Misima Island, Papua New Guinea, *Coral Reefs*, 18, 213-218, 1999.

Beck, J. W., R. L. Edwards, E. Ito, F. W. Taylor, J. Recy, F. Rougerie, P. Joannot, and C. Henin, Sea-surface temperature from coral skeletal strontium/calcium ratios, *Science*, 257, 644-647, 1992.

Benavides, L. M. and E. R. M. Druffel, Sclerosponge growth rate as determined by  $^{210}\text{Pb}$  and  $\text{D}^{14}\text{C}$  chronologies, *Coral Reefs*, 4, 221-224, 1986.

Böhm, F., M. M. Joachimski, H. Lehnert, G. Morgenroth, W. Kretschmer, J. Vaceot, and W. C. Dullo, Carbon isotope records from extant Caribbean and South Pacific sponges:

Evolution of  $\delta^{13}\text{C}$  in surface water DIC, *Earth Planetary Science Letters*, 139, 291-303, 1996.

Böhm, F., A. Haase-Schramm, A. Eisenhauer, W-C. Dullo, M.M. Joachimski, H. Lehnert, and J. Reitner, Evidence for preindustrial variations in the marine surface water carbonate system from coralline sponges, *Geochemistry, Geophysics, Geosystems*, 3: 10.1029/2001GC000264, 2002.

Boiseau, M. A., and e. al., Sr/Ca and  $\delta^{18}\text{O}$  ratios measured from *Acropora nobilis* and *Porites lutea*: Is Sr/Ca paleothermometry always reliable?, *Comptes Rendues de L'Academie des Sciences Serie II Fascicule A-Sciences do la Terre et des Planetes*, 325, 747-752, 1997.

Buddemeier, R., J. Maragos, and Knutson, Radiographic studies of reef coral exoskeletons, *J. Exp. Mar. Biol. Ecol*, 14, 179-200, 1974.

Burr, S. A., Skeletal proxies for bleaching-related stress in a scleractinian coral. Geological Society of America Annual Meeting, 2002.

Cobb, K. M., C. D. Charles, H. Cheng, and R. L. Edwards, El Niño-Southern Oscillation and tropical Pacific climate during the last millennium, *Nature*, 424, 271-276, 2003.

Cole, J. E., and R. G. Fairbanks, The Southern Oscillation recorded in the delta  $^{18}\text{O}$  of corals from Tarawa atoll, *Paleoceanography*, 5, 669-683, 1990.

Cole, J. E., R. B. Dunbar, T. R. McClanahan, N. A. Muthiga. Tropical Pacific forcing of decadal SST variability in the western Indian Ocean over the past two centuries, *Science*, 287, 617-619, 2000.

Corrège, T., T. Delcroix, J. Récy, W. Beck, G. Cabioch, and F. Le Cornec, Evidence for stronger El Niño-Southern Oscillation (ENSO) events in a mid-Holocene massive coral, *Paleoceanography*, 15, 465-470, 2000.

Corrège, T., M. K. Gagan, J. W. Beck, G. S. Burr, G. Cabioch, and F. L. Cornec, Interdecadal variation in the extent of South Pacific tropical waters during the Younger Dryas event, *Nature*, 428, 927-929, 2004.

Desenfant, F., G. F. Camoin, and A. Veron, Pollutant lead transport and input to the Caribbean during the 20th century, *Journal de Physique IV*, 107, 369-372, 2003.

deVilliers, S., B. K. Nelson, and A. R. Chivas, Biological controls on coral Sr/Ca and  $\delta^{18}\text{O}$  reconstructions of sea surface temperatures, *Science*, 269, 1995.

Dodge, R. E., and T. R. Gilbert, Chronology of lead pollution contained in banded coral skeletons, *Marine Biology*, 82, 9-13, 1984.

- Dodge, R. E., and J. C. Lang, Environmental correlates of hermatypic coral (*Montastrea annularis*) growth on the East Flower Gardens Bank, northwest Gulf of Mexico, *Limnology and Oceanography*, 28, 228-240, 1983.
- Druffel, E. M., Radiocarbon in annual coral rings from the eastern tropical Pacific Ocean, *Geophysical Research Letters*, 8, 59-62, 1981.
- Druffel, E. R. M., Geochemistry of corals: Proxies of past ocean chemistry, ocean circulation, and climate, *Proceedings of the National Academy of Sciences of the United States of America*, 94, 8354-8361, 1997.
- Druffel, E. R. M., and L. M. Benavides, Input of excess CO<sub>2</sub> to the surface ocean based on <sup>13</sup>C/<sup>12</sup>C ratios in a banded Jamaican sclerosponge, *Nature*, 321, 58-61, 1986.
- Druffel, E. R. M., and S. Griffin, Large variations of surface ocean radiocarbon: evidence of circulation changes in the southwestern Pacific, *Journal of Geophysical Research-Oceans*, 98, 20,249-20, 20249-20259, 1993.
- Druffel, E. R. M., and S. Griffin, Variability of surface ocean radiocarbon and stable isotopes in the southwestern Pacific, *Journal of Geophysical Research-Oceans*, 104, c10, 23607-23613, 1999.
- Druffel, E. M., and T. W. Linick, Radiocarbon in annual coral rings of Florida, *Geophysical Research Letters*, 5, 913-916, 1978.
- Druffel, E. R. M., S. Griffin, T. P. Guilderson, M. Kashgarian, J. Southon, and D. P. Schrag, Changes of subtropical North Pacific radiocarbon and correlation with climate variability, *Radiocarbon*, 43, 15-25, 2001.
- Dunbar, R. B., G. M. Wellington, M. W. Colgan, and P. W. Glynn, Eastern Pacific sea surface temperature since 1600 A.D.: The δ<sup>18</sup>O record of climate variability in Galapagos corals, *Paleoceanography*, 9, 291-315, 1994.
- Eakin, C. M., J. S. Feingold, and P. W. Glynn, Oil refinery impacts on coral reef communities in Aruba, N.A. in *Proceedings of the Colloquium on Global Aspects of Coral Reefs: Health, Hazards and History, 1993*, edited by Ginsberg, R. N., pp. 139-145, University of Miami, Miami, 1994.
- Eakin, C. M., M. L. Reaka-Kudla, and M. A. Chen, Growth and bioerosion of coral in the ROPME Sea Area following the 1991 Gulf Oil Spill. in *Scientific Workshop on Results of the R/V Mt. Mitchell Cruise*, Regional Organization for Protection of the Marine Environment, Kuwait, Kuwait City, 1993.
- Eakin, C. M., P. K. Swart, T. M. Quinn, K. P. Helmle, J. M. Smith, and R. E. Dodge. Application of paleoclimatology to coral reef monitoring and management, *Proceedings of the 10th International Coral Reef Symposium, Okinawa*, in press 2005.

Epstein, S., R. Buchsbaum, H. A. Lowenstam, and H. C. Urey, Revised carbonate-water isotopic temperature scale, *Bulletin of the Geological Society of America*, 64, 1315-1326, 1953.

Fairbanks, R. G., and R. E. Dodge, Annual periodicity of the  $^{18}\text{O}/^{16}\text{O}$  and  $^{13}\text{C}/^{12}\text{C}$  ratios in the coral *Montastrea annularis*, *Geochimica et Cosmochimica Acta*, 43, 1009-1020, 1979.

Fallon, S. J. M., M. T. McCulloch, R. v. Woesik, and D. J. Sinclair, Corals at their latitudinal limits: laser ablation trace element systematics in *Porites* from Shirigai Bay, Japan, *Earth and Planetary Science Letters*, 172, 221-238, 1999.

Fallon, S. J., J. C. White, and M. T. McCulloch, *Porites* corals as recorders of mining and environmental impacts: Misima Island, Papua New Guinea, *Geochimica et Cosmochimica Acta*, 66, 45-62, 2002.

Fallon, S. J., T. P. Guilderson, and K. Caldeira, Carbon isotope constraints on vertical mixing and air-sea  $\text{CO}_2$  exchange, *Geophysical Research Letters*, 30, 2289, 2003.

Felis, T., and J. Pätzold, Climate reconstructions from annually banded corals. in *Global Environmental Change in the Ocean and on Land*, edited by Shiyomi, M. et al., pp. 205-227, TERRAPUB, 2004.

Felis, T., J. Pätzold, Y. Loya, and G. Wefer, Vertical water mass mixing and plankton blooms recorded in skeletal stable carbon isotopes of a Red Sea coral, *Journal of Geophysical Research*, 103, 30731-30739, 1998.

Felis, T., J. Pätzold, Y. Loya, M. Fine, A. H. Nawar, and G. Wefer, A coral oxygen isotope record from the northern Red Sea □ documenting NAO, ENSO, and North Pacific teleconnections □ on Middle East climate variability since the year 1750, *Paleoceanography*, 15(6), 679–694, 2000.

Felis, T., G. Lohmann, H. Kuhnert, S. J. Lorenz, D. Scholz, J. Pätzold, S. A. Al-Rousan, and S. M. Al-Moghrabi, Increased seasonality in Middle East temperatures during the last interglacial period, *Nature*, 429, 164-168, 2004.

Gagan, M. K., L. K. Ayliffe, D. Hopley, J. A. Cali, G. E. Mortimer, J. Chappell, M. T. McCulloch, and M. J. Head, Temperature and surface-ocean water balance of the mid-Holocene tropical western Pacific, *Science*, 279: 1014-1018, 1998.

Gagan, M. K., L. K. Ayliffe, J. W. Beck, J. E. Cole, E. R. M. Druffel, R. B. Dunbar, and D. P. Schrag, New views of tropical paleoclimates from corals, *Quaternary Science Reviews*, 19, 45-64, 2000.

- Gagan, M. K., E. J. Hendy, S. G. Haberle, and W. S. Hantoro, Post-glacial evolution of the Indo-Pacific Warm Pool and El Nino-Southern Oscillation, *Quaternary International*, 118-19, 127-143, 2004.
- Gaillardet, J. and C. J. Allègre, Boron isotopic compositions of corals: seawater or diagenesis record? *Earth Planetary Science Letters*, 136, 665-676, 1995.
- Goodkin, N. F., K. A. Hughen, A. L. Cohen, and S. R. Smith, Record of Little Ice Age sea surface temperatures at Bermuda using a growth-dependent calibration of coral Sr/Ca, *Paleoceanography*, 20, PA4016, doi:10.1029/2005PA001140, 2005.
- Grottoli, A. G., Variability of stable isotopes and maximum linear extension in reef-coral skeletons at Kaneohe Bay, Hawaii, *Marine Biology*, 135, 437-449, 1999.
- Grottoli, A. G., Stable carbon isotopes ( $\delta^{13}\text{C}$ ) in coral skeletons, *Oceanography*, 13, 93-97, 2000.
- Grottoli, A. G., Climate: Past climate from corals. in *Encyclopedia of Ocean Sciences*, edited by Steele, J., S. Thorpe and K. Turekian, pp. 2098-2107, Academic Press, London, 2001.
- Grottoli, A. G., Effect of light and brine shrimp on skeletal  $\delta^{13}\text{C}$  in the Hawaiian coral *Porites compressa*: a tank experiment, *Geochimica et Cosmochimica Acta*, 66, 1955-1967, 2002.
- Grottoli, A. G., Monthly resolved stable oxygen isotope record in a Palauan sclerosponge *Acanthocheatetes wellsi* for the period 1977-2001, *Proceedings of the 10th International Coral Reef Symposium, Okinawa*, in press.
- Grottoli, A. G., and G. M. Wellington, Effect of light and zooplankton on skeletal  $\delta^{13}\text{C}$  values in the eastern Pacific corals *Pavona clavus* and *Pavona gigantea*, *Coral Reefs*, 18, 29-41, 1999.
- Grottoli, A. G., S. T. Gille, E. R. M. Druffel, and R. D. B. Dunbar, Decadal timescale shift in a central equatorial Pacific coral radiocarbon record, *Radiocarbon*, 45, 91-99, 2003.
- Grottoli, A. G., L. J. Rodrigues, and C. Juarez, Lipids and stable carbon isotopes in two species of Hawaiian corals, *Porites compressa* and *Montipora verrucosa*, following a bleaching event., *Marine Biology*, 145, 621-631, 2004.
- Gruber, N., and C. D. Keeling, An improved estimate of the isotopic air-sea disequilibrium of  $\text{CO}_2$ : Implications for the oceanic uptake of anthropogenic  $\text{CO}_2$ , *Geophysical Research Letters*, 28, 555-558, 2001.

Grumet, N. S., N. J. Abram, J. W. Beck, R. B. Dunbar, M. K. Gagan, T. P. Guilderson, W. S. Hantoro, and B. W. Suwargadi, Coral radiocarbon records of Indian Ocean water mass mixing and wind-induced upwelling along the coast of Sumatra, Indonesia, *Journal of Geophysical Research-Oceans*, 109, 2004.

Guilderson, T. P., and D. P. Schrag, Radiocarbon variability in the western equatorial Pacific inferred from a high-resolution coral record from Nauru Island, *Journal of Geophysical Research*, 103, 24,641-624,650, 1998a.

Guilderson, T. P., and D. P. Schrag, Abrupt shift in subsurface temperatures in the tropical Pacific associated with changes in El Niño, *Science*, 281, 240-243, 1998b.

Guilderson, T. P., D. P. Schrag, E. Goddard, M. Kashgarian, G. M. Wellington, and B. K. Linsley, Southwest subtropical Pacific surface water radiocarbon in a high-resolution coral, *Radiocarbon*, 42, 249-256, 2000.

Guilderson, T. P., D. P. Schrag, and M. A. Cane, Surface water mixing in the Solomon Sea as documented by a high-resolution coral  $^{14}\text{C}$  record, *Journal of Climate*, 17, 1147-1156, 2004.

Haase-Schramm, A., F. Böhm, A. Eisenhauer, W. C. Dullo, M. M. Joachimski, B. Hansen, and J. Reitner, Sr/Ca ratios and oxygen isotopes from sclerosponges: Temperature history of the Caribbean mixed layer and thermocline during the Little Ice Age, *Paleoceanography*, 18, 2003.

Halley R. B., P. W. Swart, R. E. Dodge, and J. H. Hudson, Decade-scale trend in seawater salinity revealed through delta  $^{18}\text{O}$  of *Montastrea annularis* annual growth bands. *Bulletin of Marine Science*, 54, 670-678, 1994.

Heimann, M., and E. Maier-Reimer, On the relations between the oceanic uptake of  $\text{CO}_2$  and its carbon isotopes, *Global Biogeochemical Cycles*, 10, 89-110, 1996.

Hendy, E. J., M. K. Gagan, C. A. Alibert, M. T. McCulloch, J. M. Lough, and P. J. Isdale, Abrupt decrease in tropical Pacific Sea surface salinity at end of Little Ice Age, *Science*, 295, 1511-1514, 2002.

Hönisch, B., N. G. Hemming, A. G. Grottoli, A. Amat, G. N. Hanson, and J. Bijma, Assessing scleractinian corals as recorders for paleo-pH: Empirical calibration and vital effects, *Geochimica et Cosmochimica Acta*, 68, 3675-3685, 2004.

Hudson, J. H., Growth rates in *Montastrea annularis* : a record of environmental change in Key Largo Coral Reef Marine Sanctuary, Florida, *Bulletin of Marine Science*, 31, 444-459, 1981.

Hudson, J. H., E. A. Shinn, R. B. Halley, and B. Lidz, Sclerochronology: a tool for interpreting past environments, *Geology*, 4, 361-364, 1976.

Hudson, J. H., G. V. N. Powell, M. B. Robblee, and T. J. Smith III, A 107-year-old coral from Florida Bay: barometer of natural and man-induced catastrophes?, *Bulletin of Marine Science*, 44, 283-291, 1989.

Hughes, G. B. and C. W. Thayer, Sclerosponges: potential high-resolution recorders of marine paleotemperatures. In *Geological perspectives of global climate change*, edited by Gerhard, L. C., W. E. Harrison and B. M. Hanson, pp. 137-151, AAPG Studies in Geology, Tulsa, OK, 2001.

Isdale, P., Fluorescent bands in massive corals record centuries of coastal rainfall, *Nature*, 310, 578-579, 1984.

Isdale, P. J., B. J. Stewart, and J. M. Lough, Palaeohydrological variation in a tropical river catchment: a reconstruction using fluorescent bands in corals of the Great Barrier Reef, Australia, *The Holocene*, 8, 1-8, 1998.

Joachimski, M. M., F. Böhm, and H. Lehnert, Longterm isotopic trends from Caribbean desmosponges: evidence for isotopic disequilibrium between surface waters and atmosphere., *Proceedings of the 2nd European Regional Meeting ISRS*, 29, 141-147, 1995.

Kheshgi, H. S., A. K. Jain, and D. J. Wuebbles, Model-based estimation of the global carbon budget and its uncertainty from carbon dioxide and carbon isotope records, *Journal of Geophysical Research*, 104, 31127-31143, 1999.

Kim, S. -T., and J. R. O'Neil, Temperature dependence of  $\delta^{18}\text{O}$ , *Geochimica et Cosmochimica Acta*, 61, 3461-3475, 1997.

Klein, R., Y. Loya, G. Gvirtzman, P. Isdale, and M. Susic, Seasonal rainfall in the Sinai Desert during the late Quaternary inferred from fluorescent bands in fossil corals, *Nature*, 345, 145-150, 1990.

Kleypas, J. A., and C. Langdon, Chapter 5: Coral Reefs and Changing Seawater Chemistry, *Corals and Climate Change, Geophysical Monographs*, American Geophysical Union, Washington, DC, this volume.

Kleypas, J.A., R.A. Feely, V.J. Fabry, C. Langdon, C.L. Sabine, and L.L. Robbins. Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research, report of a workshop held 18–20 April 2005, St. Petersburg, FL, sponsored by NSF, NOAA, and the U.S. Geological Survey, 88 pp., 2006.

Knutson, D. W., R. W. Buddemeier, and S. V. Smith, Coral chronometers: seasonal growth bands in reef corals, *Science*, 177, 270-272, 1972.

- Kortzinger, A., P. D. Quay, and R. E. Sonnerup, Relationship between anthropogenic CO<sub>2</sub> and the <sup>13</sup>C Suess effect in the North Atlantic Ocean, *Global Biogeochemical Cycles*, 17, 1005, doi: 10.1029/2001GB001427,002003, 2003.
- Lazareth, C., P. Willenz, J. Navez, E. Keppens, F. Dehairs, and L. Andre, Sclerosponges as a new potential recorder of environmental changes: Lead in *Ceratoporella nicholsoni*, *Geology*, 28, 515-518, 2000.
- Le Bec, N., A. Juillet-Leclerc, T. Corrège, D. Blamart, and T. Delcroix, A coral δ<sup>18</sup>O record of ENSO driven sea surface salinity variability in Fiji (south-western tropical Pacific), *Geophysical Research Letters*, 27, 3897-3900, 2000.
- Leder, J. J., A. M. Szmant, and P. K. Swart, The effect of prolonged "bleaching" on skeletal banding and stable isotope composition in *Montastrea annularis*. Preliminary observations, *Coral Reefs*, 10, 19-27, 1991.
- Linsley, B., R. Messier, and R. Dunbar, Assessing between colony oxygen isotope variability in the coral *Porites lobata* at Clipperton Atoll, *Coral Reefs*, 18, 13-27, 1999.
- Linsley, B. K., G. M. Wellington, D. P. Schrag, L. Ren, M. J. Salinger, and A. W. Tudhope, Geochemical evidence from corals for changes in the amplitude and spatial pattern of South Pacific interdecadal climate variability over the last 300 years, *Climate Dynamics*, 22, 1-11, 2004.
- Liu, G., A. E. Strong, W. Skirving, L. F. Arzayus. Overview of NOAA Coral Reef Watch Program's near-real-time satellite global coral bleaching monitoring activities, *Proceedings of the 10th International Coral Reef Symposium, Okinawa*, in press 2005.
- Lough, J. M., A strategy to improve the contribution of coral data to high-resolution paleoclimatology, *Palaeogeography, Palaeoclimatology and Palaeoecology*, 204, 115-143, 2004.
- Lough, J. M., and D.J. Barnes, Several centuries of variation in skeletal extension, density and calcification in massive *Porites* colonies from the Great Barrier Reef: a proxy for seawater temperature and a background of variability against which to identify unnatural change, *Journal of Experimental Marine Biology and Ecology*, 211, 29-67, 1997.
- Lough, J. M., D. J. Barnes, and F. A. McAllister, Luminescent lines in corals from the Great Barrier Reef provide spatial and temporal records of reefs affected by land runoff, *Coral Reefs*, 21, 333-343, 2002.
- Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Amer. Meteorol. Soc.*, 78, 1069-1079, 1997.

Marshall, J. F., and M. T. McCulloch, An assessment of the Sr/Ca ratio in shallow water hermatypic corals as a proxy for sea surface temperature, *Geochimica et Cosmochimica Acta*, 66, 3263-3280, 2002.

McConnaughey, T.,  $^{13}\text{C}$  and  $^{18}\text{O}$  isotopic disequilibrium in biological carbonates: I. Patterns, *Geochimica et Cosmochimica Acta*, 53, 151-162, 1989a.

McConnaughey, T.,  $^{13}\text{C}$  and  $^{18}\text{O}$  isotopic disequilibrium in biological carbonates: II. *In vitro* simulation of kinetic isotope effects, *Geochimica et Cosmochimica Acta*, 53, 163-171, 1989b.

McCulloch, M. T., and T. Esat, The coral record of last interglacial sea levels and sea surface temperatures, *Chemical Geology*, 169, 107-129, 2000.

McCulloch, M. T., M. K. Gagan, G. E. Mortimer, A. R. Chivas, and P. J. Isdale, A high-resolution Sr/Ca and  $\delta^{18}\text{O}$  coral record from the Great Barrier Reef, Australia, and the 1982-1983 El Niño, *Geochimica et Cosmochimica Acta*, 58, 2747-2754, 1994.

McCulloch, M., G. Mortimer, T. Esat, L. Xianhua, B. Pillans, and J. Chappell, High resolution windows into early Holocene climate: Sr/Ca coral records from the Huon Peninsula, *Earth and Planetary Science Letters*, 138, 169-178, 1996.

McCulloch, M. T., A. W. Tudhope, T. M. Esat, G. E. Mortimer, J. Chappell, B. Pillans, A. R. Chivas, and A. Omura, Coral record of equatorial sea-surface temperatures during the penultimate deglaciation at Huon Peninsula, *Science*, 283, 202-204, 1999.

McCulloch, M., S. Fallon, T. Wyndham, E. Hendy, J. Lough, and D. Barnes, Coral record of increased sediment flux to the inner Great Barrier Reef since European settlement, *Nature*, 421, 727-730, 2003.

Medina-Elizalde, M., G. Gold-Bouchot, and V. Ceja-Moreno, Lead contamination in the Mexican Caribbean recorded by the coral *Montastrea annularis* (Ellis and Solander), *Marine Pollution Bulletin*, 44, 2002.

Meibom, A., J. Cuif, F. Hillion, B. R. Constantz, A. Juillet-Leclerc, Y. Dauphin, T. Watanabe, and R. B. Dunbar (2004), Distribution of magnesium in coral skeleton, *Geophysical Research Letters*, 31, L23306, doi:10.1029/2004GL021313.

Min, G. R., R. L. Edwards, F. W. Taylor, J. Recy, C. D. Gallup, and J. W. Beck, Annual cycles of U/Ca in coral skeletons and U/Ca thermometry, *Geochimica et Cosmochimica Acta*, 59, 2025-2042, 1995.

Mitsuguchi, T., E. Matsumoto, O. Abe, T. Uchida, and P. J. Isdale, Mg/Ca thermometry in coral skeletons, *Science*, 274, 961-963, 1996.

Moore, M. D., C. D. Charles, J. L. Rubenstone, and R. G. Fairbanks, U/Th-dated sclerosponges from the Indonesian Seaway record subsurface adjustments to west Pacific winds, *Paleoceanography*, 15, 404-416, 2000.

Moustafa, Y. A., J. Pätzold, Y. Loya, and G. Wefer, Mid-Holocene stable isotope record of corals from the northern Red Sea, *International Journal of Earth Sciences*, 88, 742-751, 2000.

Nyberg, J., Luminescence intensity in coral skeletons from Mona Island in the Caribbean Sea and its link to precipitation and wind speed, *Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences*, 360, 749-766, 2002.

Pätzold, J., T. Bickert, B. Flemming, H. Grobe, and G. Wefer, Holozänes klima des Nordatlantiks rekonstruiert aus massiven korallen von Bermuda, *Natur und Museum*, 129, 165-177, 1999.

Pelejero, C., E. Calvo, M. T. McCulloch, J. F. Marshall, M. K. Gagan, J. M. Lough, and B. N. Opdyke, Preindustrial to modern interdecadal variability in coral reef pH, *Science*, 309: 2204-2207, 2005.

Peng, Z. C., X. X. He, Z. F. Zhang, J. Zhou, L. S. Sheng, and H. Gao, Correlation of coral fluorescence with nearshore rainfall and runoff in Hainan Island, South China Sea, *Progress in Natural Science*, 12, 41-44, 2002.

Quadrelli, R., and J. M. Wallace, A simplified linear framework for interpreting patterns of Northern Hemisphere wintertime climate variability, *Journal of Climate*, 17, 3728-3744, 2004.

Quay, P. D., B. Tilbrook, and C. S. Wong, Oceanic uptake of fossil fuel CO<sub>2</sub>: Carbon-13 evidence, *Science*, 256, 74-79, 1992.

Quay, P. D., R. Sonnerup, T. Westby, J. Stutsman, and A. McNichol, Changes in the <sup>13</sup>C/<sup>12</sup>C of dissolved inorganic carbon in the ocean as a tracer of anthropogenic CO<sub>2</sub> uptake., *Global Biogeochemical Cycles*, 17, doi:10.1029/2001GB001817, 2003.

Quinn, T. M., and D. E. Sampson, A multiproxy approach to reconstructing sea surface conditions using coral skeleton geochemistry, *Paleoceanography*, 17, 1062, PA000528, 2002.

Reitner, J., G. Gautret, and P. Gautret, Skeletal formation in the modern but ultraconservative chaetetid sponge *Spirastrella (Acanthochaetetes) wellsi* (Demospongiae, Porifera). *Facies*, 34, 193-208, 1996.

Ren, L., B. K. Linsley, G. M. Wellington, D. P. Schrag, and O. Hoegh-Guldberg, Deconvolving the δ<sup>18</sup>O seawater component from subseasonal coral δ<sup>18</sup>O and Sr/Ca at

- Rarotonga in the southwestern subtropical Pacific for the period 1726 to 1997, *Geochimica et Cosmochimica Acta*, 67, 1609-1621, 2002.
- Reuer, M. K., E. A. Boyle, and J. E. Cole, A mid-twentieth century reduction in tropical upwelling inferred from coralline trace element proxies, *Earth and Planetary Science Letters*, 210, 437-452, 2003.
- Rosenheim, B. E., P. K. Swart, S. R. Thorrold, A. Eisenhauer, and P. Willenz, Salinity change in the subtropical Atlantic: Secular increase and teleconnections to the North Atlantic Oscillation, *Geophysical Research Letters*, 32, L02603, doi:10.1029/2004GL021499, 2005.
- Schrag, D. P., Rapid analysis of high-precision Sr/Ca ratios in scleractinian corals and other marine carbonates, *Paleoceanography*, 14, 97-102, 1999.
- Scoffin, T. P., A. W. Tudhope, and B. E. Brown, Fluorescent and skeletal density banding in *Porites lutea* from Papua New Guinea and Indonesia, *Coral Reefs*, 7, 169-178, 1989.
- Shen, G. T., and E. A. Boyle, Lead in corals: reconstruction of historical industrial fluxes to the surface ocean, *Earth and Planetary Science Letters*, 82, 289-304, 1987.
- Shen, G. T., E. A. Boyle, and D. W. Lea, Cadmium in corals as a tracer of historical upwelling and industrial fallout, *Nature*, 328, 794-796, 1987.
- Shen, G. T., and R. B. Dunbar, Environmental controls on uranium in reef corals, *Geochimica et Cosmochimica Acta*, 59, 2009-2024, 1995.
- Shen, G. T., T. M. Campbell, R. B. Dunbar, G. M. Wellington, M. W. Colgan, and P. W. Glynn, Paleochemistry of manganese in corals from the Galapagos Islands, *Coral Reefs*, 10, 91-100, 1991.
- Shen, G. T., J. E. Cole, D. W. Lea, L. J. Linn, T. A. McConnaughey, and R. G. Fairbanks, Surface ocean variability at Galápagos from 1936-1982: Calibration of geochemical tracers in corals, *Paleoceanography*, 563-588, 1992a.
- Shen, G. T., L. J. Linn, T. M. Campbell, J. E. Cole, and R. G. Fairbanks, A chemical indicator of trade wind reversal in corals from the western tropical Pacific, *Journal of Geophysical Research, C, Oceans*, 97, 12689-12697, 1992b.
- Sinclair D. J., L. P. J. Kinsley, and M. T. McCulloch, High resolution analysis of trace elements in corals by laser-ablation ICP-MS. *Geochimica et Cosmochimica Acta* 62, 1889-1901, 1998.

Slowey, N. C., and T. J. Crowley, Interdecadal variability of Northern Hemisphere circulation recorded by Gulf of Mexico corals, *Geophysical Research Letters*, 22, 2345-2348, 1995.

Smith, T. J., J. H. Hudson, M. B. Robblee, G. V. N. Powell, and P. J. Isdale, Freshwater flow from the Everglades to Florida Bay: A historical reconstruction based on fluorescent banding in the coral *Solonastrea bournoni*, *Bulletin of Marine Science*, 44, 374-282, 1989.

Solow, A. and A. Huppert, Optimal multiproxy reconstruction of sea surface temperature from corals, *Paleoceanography*, 19, PA4004, 2004.

Sonnerup, R. E., P. D. Quay, A. P. McNichol, J. L. Bullister, T. A. Westby, and H. L. Anderson, Reconstructing the oceanic  $^{13}\text{C}$  Suess effect, *Global Biogeochemical Cycles*, 13, 857-872, 1999.

Strong, A. E., G. Liu, J. Meyer, J. C. Hendee, and D. Sasko. Coral Reef Watch 2002. *Bulletin of Marine Science*, 75, 259-268, 2004.

Strong, A. E., F. Arzayus, and W. Skirving, Chapter 8: Identifying coral bleaching remotely via Coral Reef Watch – Improved integration and implications for changing climate, *Corals and Climate Change, Geophysical Monographs*, American Geophysical Union, Washington, DC, this volume.

Stuiver, M., and H. A. Polach, Discussion reporting of  $^{14}\text{C}$  data, *Radiocarbon*, 19, 355-363, 1977.

Suzuki, A., M. K. Gagan, K. Fabricius, P. J. Isdale, I. Yukino, and H. Kawahata, Skeletal isotope microprofiles of growth perturbations in *Porites* corals during the 1997-1998 mass bleaching event, *Coral Reefs*, 22, 357-369, 2003.

Swart, P. K., J. L. Rubenstone, C. D. Charles, and J. Reitner, Sclerosponges: A new proxy indicator of climate, *Rep. 12*, 19 pp., NOAA Climate and Global Change Program, 1998a.

Swart, P. K., K. S. White, D. Enfield, R. E. Dodge, and P. Milne, Stable oxygen isotopic composition of corals from the Gulf of Guinea as indicators of periods of extreme precipitation conditions in the sub-Sahara, *Journal of Geophysical Research*, 103, 27885-27891, 1998b.

Swart, P. K., G. Healy, L. Greer, M. Lutz, A. Saied, D. Anderegg, R. E. Dodge, and D. Rudnick, The use of proxy chemical records in coral skeletons to ascertain past environmental conditions in Florida Bay, *Estuaries*, 22, 384-397, 1999.

Swart, P. K., S. Thorrold, B. Rosenheim, A. Eisenhauer, C. G. A. Harrison, M. Grammer, and C. Latkoczy, Intra-annual variation in the stable oxygen and carbon and trace

element composition of sclerosponges, *Paleoceanography*, 17, 1045, doi:10.1029/2000PA000622, 2002.

Tans, P. P., J. A. Berry, and R. F. Keeling, Oceanic  $^{13}\text{C}/^{12}\text{C}$  observations: A new window on ocean  $\text{CO}_2$  uptake, *Global Biogeochemical Cycles*, 7, 353-368, 1993.

Theodorou, N. K., The enigmatic properties of fluorescent banding in massive corals of the species *Porites lutea* from Phuket, Thailand, Ph.D., The University of Edinburgh, 1995.

Toler, S. K., and P. Hallock, Shell malformation in stressed *Amphistegina* populations: Relation to biomineralization and paleoenvironmental potential, *Marine Micropaleontology*, 34, 107-115, 1998.

Tudhope, A. W., G. B. Shimmield, C. P. Chilcott, M. Jebb, A. E. Fallick, and A. N. Dalglish, Recent changes in climate in the far western equatorial Pacific and their relationship to the Southern Oscillation: oxygen isotope records from massive corals, Papua New Guinea, *Earth and Planetary Science Letters*, 136, 575-590, 1995.

Tudhope, A. W., D. W. Lea, G. B. Shimmield, C. P. Chilcott, and S. Head, Monsoon climate and Arabian sea coastal upwelling recorded in massive corals from southern Oman, *Palaios*, 11, 347-361, 1996.

Tudhope, A. W., C. P. Chilcott, M. T. McCulloch, E. R. Cook, J. Chappell, R. M. Ellam, D. W. Lea, J. M. Lough, and G. B. Shimmield, Variability in the El Niño–Southern Oscillation through a glacial-interglacial cycle, *Science*, 291, 1511-1517, 2001.

Vogel, J. S., D. E. Nelson, and J. R. Southon,  $^{14}\text{C}$  background levels in an accelerator mass spectrometry system, *Radiocarbon*, 29, 323-333, 1987.

Weber, J. N., Incorporation of strontium into reef coral skeletal carbonate, *Geochimica et Cosmochimica*, 2173-2190, 1973.

Weber, J. N., and P. M. J. Woodhead, Temperature dependence of Oxygen-18 concentration in reef coral carbonates, *Journal of Geophysical Research*, 77, 463-473, 1972.

Weber, J. N., E. W. White, and P. H. Weber, Correlation of density banding in reef coral skeletons with environmental parameters: the basis for interpretations of chronological records preserved in the coralla of corals, *Paleobiology*, 1, 137-149, 1975.

Wellington, G. M., and R. B. Dunbar, Stable isotopic signature of El-Nino Southern Oscillation events in eastern tropical Pacific reef corals, *Coral Reefs*, 14, 5-25, 1995.

Wellington, G. M., G. Merlen, and R. B. Dunbar, Calibration of stable oxygen isotope signatures in Galapagos corals, *Paleoceanography*, 11, 467-480 1996.

Wild, F. J., A. C. Jones, and A. W. Tudhope, Investigation of luminescent banding in solid coral: the contribution of phosphorescence, *Coral Reefs*, 19, 132-140, 2000.

Willenz, P. and W. D. Hartmen, Calcification rate of *Ceratoporella nicholsoni* (Porifera: sclerospongiae): an *in situ* study with calcein Proceedings of the 5th International Coral Reef Congress, Tahiti, pp 113-118, 1985.

Woodroffe, C. D., and M. K. Gagan, Coral microatolls from the central Pacific record late Holocene El Nino, *Geophysical Research Letters*, 27, 1511-1514, 2000.

Woodroffe, C. D., M. R. Beech, and M. K. Gagan, Mid-late Holocene El Nino variability in the equatorial Pacific from coral microatolls, *Geophysical Research Letters*, 30, 2003.

Wörheide, G., P. Gautret, J. Reitner, F. Böhm, M. M. Joachimski, V. Thiel, W. Michaelis, and M. Massault, Basal skeletal formation, role and preservation of intracrystalline organic matrices, and isotopic record in the coralline sponge *Astrosclera willeyana* Lister, 1900, *Boletin De La Real Sociedad Espanola De Historia Natural, Seccion Geologica*, 91, 355-374, 1997.

Yu, K. F., J. X. Zhao, T. S. Liu, G. H. Wei, P. X. Wang, and K. D. Collerson, High-frequency winter cooling and reef coral mortality during the Holocene climatic optimum, *Earth and Planetary Science Letters*, 224, 143-155, 2004.