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# Application of Paleoclimatology to Coral Reef Monitoring and Management

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**Abstract** The skeletons of reef-building corals are valuable archives of climatic and environmental information. Paleoclimatic data chiefly have been generated in areas most sensitive to global or regional climatic variability. However, these records also provide valuable information on anthropogenic influences – guidance of value to resource managers. NOAA's Coral Reef Watch targets observations of current and past coral reef health in or near marine protected areas through satellites, *in situ* sensor platforms, and paleoclimatic analyses. Paleoclimatic data provide retrospective monitoring through multi-century environmental reconstructions that improve our understanding of past stress to coral reefs. Two sites in the Florida Keys National Marine Sanctuary were the first to benefit from Coral Reef Watch Program paleoenvironmental analyses. Coral cores yielded direct measurements of $\delta^{18}$O, $\delta^{13}$C, Sr/Ca, and coral skeletal growth (extension, density, and calcification) and reconstructions of reef temperatures. Temperature reconstructions were compared with instrumental data from nearby stations and global data sets, while skeletal growth was used to infer responses to changing climatic and environmental conditions. Differences between paleoclimatic data and gridded datasets demonstrated that paleodata provide more accurate estimates of reef temperatures as they sample subsurface temperatures where the corals live. Because of relatively high thermal variability, at least 12 samples per year are needed at these sites. Further work will extend these records back in time, to new locations, and expand on the data reconstructed from the skeletal archives.

**Keywords** coral paleoclimatology, Florida Keys National Marine Sanctuary, geochemistry, sclerochronology, Coral Reef Watch, *Montastraea faveolata*

## Introduction

Coral skeletons serve as excellent recorders of paleoenvironmental conditions in tropical nearshore waters. The $\delta^{18}$O values of coral skeletons record a mix of temperature and salinity while Sr/Ca ratios reflect primarily temperature (Fairbanks and Dodge 1979; Leder et al. 1996; McConnaughey 1987a, 1987b; Weber and Woodhead 1972; Weil et al. 1981). These relationships are quite robust, although stressed corals, slow coral growth, and variations in productivity in coral endosymbiotes may result in deviations from established calibrations for Sr/Ca (deVilliers et al. 1995; Marshall and McCulloch 2002; Cohen et al. 2002; Cohen and Sohn 2004). More recently, a combination of Sr/Ca and $\delta^{18}$O has been used to reconstructed salinity (McCulloch et al. 1994; Le Bec et al. 2000; Quinn and Sampson 2002; Rohling and Bigg 1998; Swart et al. 1999; Swart et al. 1998) and ocean mixing (Guilderson et al. 2000). Similar to the use of tree rings, scientists also have used the growth of coral skeletons as indicators of other forms of environmental conditions (Barnes and Lough 1993; Dodge and Vaisnys 1975; Draschba et al. 2000; Hudson et al. 1976; Lough and Barnes 1990; Klein et al. 1992; Slowey and Crowley 1995; Wellington and Glynn 1983). Despite the value of coral skeletons, as well as other paleoclimatic proxies, as recorders of past climate and environmental stress, they typically have been considered as interesting research products and have not been included as part of monitoring programs. As a result, of 88 coral paleo data sets in the holdings of the World Data Center for Paleoclimatology on 1 July 2004, only 4 were from areas of U.S. management interest (NCDC 2005).

The U.S. National Oceanic and Atmospheric Administration (NOAA) recently developed an integrated program of monitoring coral reefs. The Coral Reef Watch (NOAA 2005) includes a wide range of observations on coral reefs. In addition to dedicated satellite products (Strong et al. 1997) and *in situ* sensor platforms (Hendee et al. 2002), this program includes the novel addition of paleoclimatic data from the corals themselves. Monitoring of climatic data from reef environments typically extends back only a decade or so. Unfortunately, the onset of widespread coral bleaching occurred before such monitoring was in place in many locations. By implementing a program of "retrospective" monitoring through coral paleoclimatic records, we can reconstruct *in situ* records of temperature variability on reefs in the time before monitoring was implemented. The Coral Reef Watch program provides for coral reef environmental data on a wide range of timescales, from near real-time *in situ* and satellite data through centuries-long paleoclimatic data. This allows us to understand the history of climatic variability under which corals have lived and to better understand recent changes, including recent increases in coral bleaching. Work by Winter et al. (2000) indicated that water temperatures in the Caribbean during the 20$^{th}$ century might be significantly higher than earlier centuries. If this is true, it could have important implications for understanding the recent increase in bleaching observations and managing the resources accordingly.

Coral bleaching observations are now recognized as an important part of NOAA's coral reef observations and is an integral part of the now expanding Coral Reef Ecosystem Integrated Observing System (CREIOS). This paper documents the first paleoclimatic data to emerge directly from the NOAA Coral Reef Watch-Paleo project. Their unique importance lies in two areas. The first is the application of paleoclimatic records as part of a multidisciplinary monitoring program targeted at sites that were either recently instrumented with *in situ* monitoring arrays or were planned for future monitoring installations. The other was that the reefs under study were targeted because they provide climatic histories for a marine protected area. This was important because most funding for paleoclimatic research has been limited to sites chosen to target large-scale climate patterns such as the El Niño-Southern Oscillation. Funding previously has not been available for developing paleoclimatic records to benefit marine protected area management. This paper documents records from two sites in the Florida Keys National Marine Sanctuary (FKNMS). In addition to developing multi-decadal records, this project included an investigation into the sampling resolution necessary for capturing the optimal levels of environmental variability from the sites.

## Materials and Methods

The Florida Keys National Marine Sanctuary was chosen as the first site for paleoclimatic work under Coral Reef Watch because of its long existing ocean temperature records from multiple overlapping efforts (Fig. 1). The oldest involves the use of logging in situ temperature recorders placed in various locations on reefs by Harold Hudson (pers. comm.). Records used in this study covered 1990-99 at Looe Key and were collected using Ryan TempMentor loggers that were later replaced by SeaBird loggers.

Permanent navigational markers in the Florida Keys were instrumented through the National Oceanic and Atmospheric Administration's Coastal-Marine Automated Network (C-MAN) that was established by the NOAA National Data Buoy Center in the early 1980's (NRC 1998; NODC 2005). C-MAN stations primarily monitor surface meteorological variables, with surface water temperature added later at select sites – in the late 1980s in the Florida Keys. These were supplemented starting in 1989 through the Florida Institute of Oceanography's Sustained Ecological Research Related to the Management of the Florida Keys Seascape (SEAKEYS) project that enhanced instruments

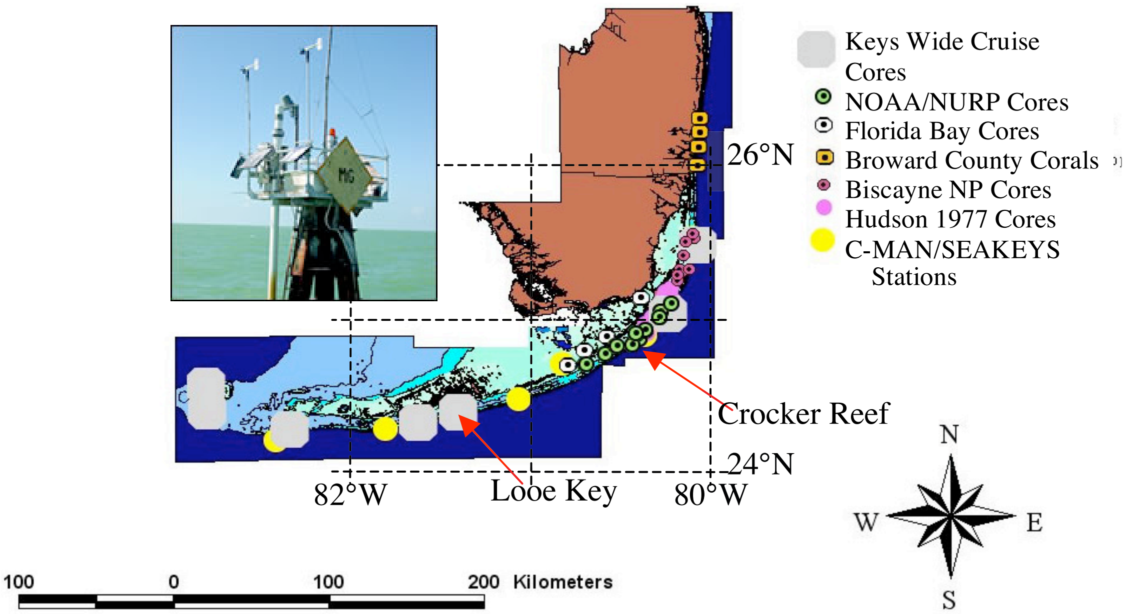


Fig. 1. Map showing cores and *in situ* stations available for paleoclimatic analysis in the Florida Keys and southeastern Florida, noting the two sites in this study and the approximate scale of 1x1° gridded data sets. Superimposed is an image of a SEAKEYS station (from FIO 2004).

on six C-MAN stations in the Florida Keys (FIO 2005; Humphrey et al. 1999). In addition to surface meteorological variables, select SEAKEYS stations contain additional subsurface (1-3m depth) oceanographic sensors including sea temperature, salinity, terrestrial solar irradiance, sea level, transmissometer, and fluorometer. C-MAN SEAKEYS data used in this study covered 1988-2002 from the station nearest Looe Key (Sombrero Reef station SMKF1, 24.63°N, 81.11°W, 32 km distance) and 1987-1996 at the station nearest Crocker Reef (Molasses Reef station MLRF1, 25.01°N, 80.38°W, 18 km distance). Additionally, data were available for the Florida Keys by extracting grid points from gridded satellite and *in situ* reconstructed data sets. Gridded data were extracted from two data sets: the NOAA Optimum Interpolation Sea Surface Temperature (OI-SST) V2, formerly known as the Reynolds SST data set (Reynolds et al. 2002), and the U.K. Met Office - HadISST 1.1 - Global sea Ice Coverage and Sea Surface Temperature data (Rayner et al. 2003). Both of these provide data in 1° x 1° grids. In all cases, instrumental datasets were binned into average values covering approximately 12 equally spaced samples per year to match the sampling resolution of the coral cores. Comparisons of coral sampling resolution with instrumental data were used to evaluate the appropriate sampling resolution for this project in the future.

Cores used for this project were Looe Key (24.55°N, 81.42°W) cores LK1 and LK23 collected in August 2002 by Harold Hudson, and Crocker Reef (24.90°N, 80.52°W) core NN23 collected in June 1998 from next to the park buoy near Molasses Reef off Key Largo during the NOAA/National Undersea Research Center cruise (Fig. 2). All cores are of *Montastraea faveolata* Ellis & Solander 1786 and were cut into parallel-sided slabs, X-radiographed, and digitized for relative optical densitometry measurements (Helmle pers. comm..). Growth characteristics (extension, density, and calcification) were analyzed at Nova Southeastern University Oceanographic Center National Coral Reef Institute.

Continuous samples were drilled for geochemical analysis from the core slab that was best aligned with each coral's growth axis. The Crocker Reef core was analyzed for stable carbon and oxygen isotopic composition using a Kiel device interfaced with a Delta plus stable isotope mass spectrometer. Reproducibility using this instrument was approximately 0.05 and 0.08‰ for $\delta^{13}C$ and $\delta^{18}O$ respectively. Data were calibrated relative to the Vienna Peedee Belemnite Limestone standard (VPDB) and reported in the conventional notation. The Sr/Ca ratios from the Looe Key coral were analyzed on a Perkin-Elmer 4300 DV ICP-OES using the techniques of Schrag (1999). Precision of the Sr/Ca determinations on the Looe Key coral is estimated to be ± 0.18% (2σ; 0.03 mmol/mol) based on repeated analyses of a coral solution standard. Looe Key Sr/Ca data were used to reconstruct ocean temperatures through calibration against a combined dataset using the Hudson logger data with variance-scaled HadISST data used to interpolate the missing periods from the logger data. Looe Key temperature reconstruction was performed using the reduced major axis regression technique (Davis 2002).

**Results**

Because multiple sets of instrumental data were available for calibration, it was possible to compare these to determine which were most applicable as indicators of reef temperatures. The following results from the two sites provide calibration and long records of environmental variability from the two sites, as well as coral growth records from Crocker Reef.

*Looe Key:* When the gridded data sets were compared with the *in situ* data sets from the C-MAN/SEAKEYS and Hudson loggers, it was clear that the gridded datasets did not capture most of the colder winter temperatures and some of the warmer summer temperatures observed by the subsurface loggers (Fig. 3). Correlations among all data sets were high (Table 1).

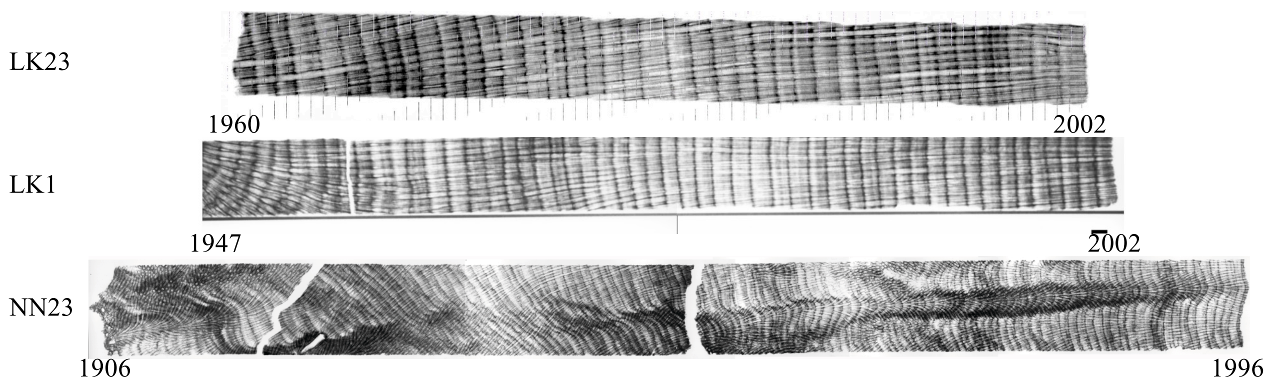


Fig. 2. X-radiographic positives of Looe Key cores LK23, LK1, and Crocker Reef core NN23 (top to bottom, not to equal scale). LK23 contained 42 years of record, LK1 55 years, and NN23 91 years. Average extension of the Looe Key cores was approximately 5.3 mm/y and extension at Crocker Reef was approximately 8.4 mm/y.

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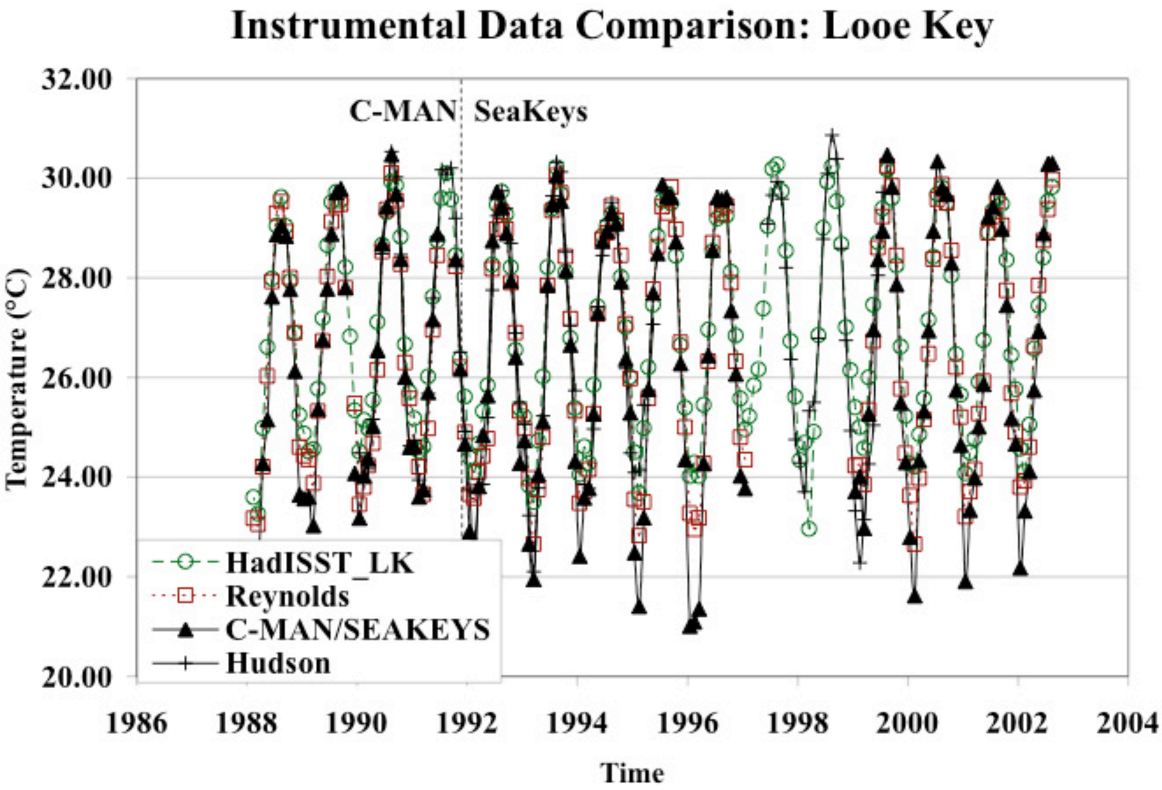


Fig. 3. Comparison of instrumental data for Looe Key: U.K. Met Office HadISST and NOAA OI-SST V2 gridded data for the grid point that included Looe Key, Sombrero Reef C-MAN surface and SEAKEYS near-surface ocean temperature sensors, and Harold Hudson's Looe Key temperature loggers. All data were averaged into 12 mean samples per year. Note the line that designates the switch from C-MAN to SEAKEYS instruments.

| **Bias and ($r^2$)** | HadISST | C-MAN / SEAKEYS | Hudson | Paleo mean |
|---|---|---|---|---|
| Reynolds | -0.37 (0.98) | 0.25 (0.97) | 0.02 (0.92) | - 0.30 (0.82) |
| HadISST | | 0.62 (0.97) | 0.33 (0.92) | 0.23 (0.81) |
| C-MAN / SEAKEYS | | | - 0.13 (0.91) | - 0.55 (0.84) |
| Hudson | | | | - 0.02 (0.81) |

Table 1. Bias comparisons and correlation $r^2$ of Looe Key temperature datasets. Bias is calculated as the average difference between the datasets across the left minus the datasets across the top in °C. Paleo mean is the mean of the SSTs calculated from Sr/Ca data from cores LK1 and LK 23. All correlations are highly significant at $P << 0.0001$.

Not surprisingly, the highest correlations were between the two gridded data sets as they share similar source data and techniques. Both gridded data sets also correlated higher with the C-MAN/ SEAKEYS data than with the Hudson loggers or the paleodata (mean of Sr/Ca reconstructed SSTs from LK1 and LK23). This was also consistent with the nature of the records as all are primarily taken from near-surface waters. While all the instrumental data sets correlated at better than 0.8 with the paleo reconstructed temperatures, it was a bit surprising that the lowest correlations were between the paleodata and the HadISST and Hudson datasets that were used to calibrate the paleo records.

Substantial biases were found when comparing the data sets. HadISST data were over 0.6°C warmer than the C-MAN/SEAKEYS and over 0.3°C warmer than the Hudson loggers on average (Table 1). This indicated that the order of preference for calibration should be the on-site loggers, then nearby surface stations, then gridded datasets. During the 1988-2002 period of *in situ* instrumental records, the usual temperature range at this site was approximately 7°C with almost 10°C total annual range. At the time of writing this paper, coral proxy data from Looe Key were limited to two short cores of 42 and 55 years in coverage (Fig. 4).

Because the cores fully overlapped the period of coverage of reliable HadISST data, these records provided a valuable test against which to compare the paleodata. The corals exhibited a cool bias relative to the HadISST data. In Fig. 4 this was seen as a tendency for few of the HadISST data to fall below the values from the cores except in the late 1950s and for many of the HadISST data to lie above the coral data. This bias of 0.23°C (Table 1) was consistent with the warm bias of the HadISST data when compared to the *in situ* instruments. Ongoing work by Coral Reef Watch-Paleo will soon provide longer reef temperature records from Looe Key.

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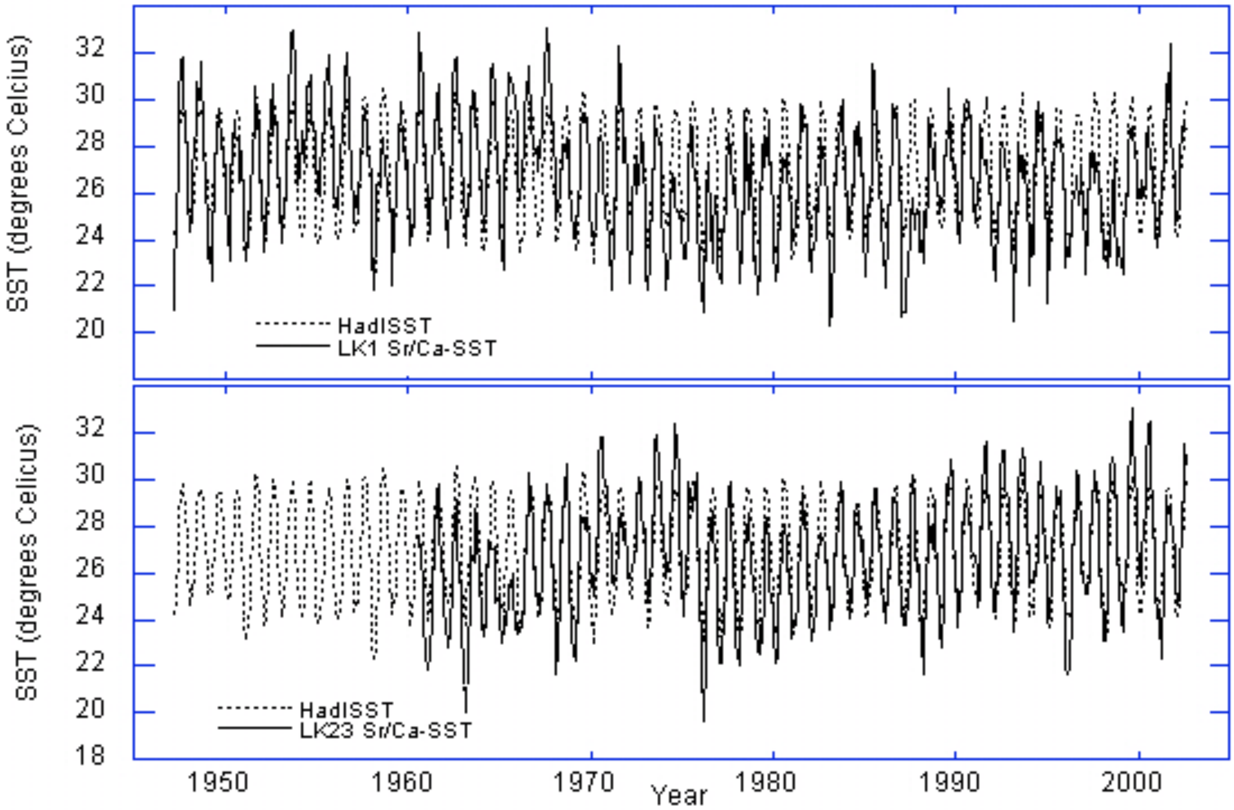


Fig. 4. Comparison of ocean temperature data from two cores from Looe Key (reconstruction from Sr/Ca ratios) with U.K. Met Office HadISST gridded data. All data were averaged into 12 mean samples per year.

*Crocker Reef:* A century-long record of $\delta^{18}O$ was produced from the coral collected from Crocker Reef. A comparison of the $\delta^{18}O$ with ocean temperature from the nearby C-MAN/SEAKEYS station is shown in Fig. 5. The Crocker Reef $\delta^{18}O$ were not as highly correlated with temperature ($r^2 = 0.44$) as were the Looe Key Sr/Ca data. The change in $\delta^{18}O$ was 0.4‰ for every 1°C change in temperature, significantly greater than that observed by Leder et al. (1996). In viewing the long Crocker Reef record of $\delta^{18}O$ (Fig. 6), it was apparent that there has not been a major shift in oxygen isotopes in the core. The decades of the 1930s through 1960s appear to have slightly lower $\delta^{18}O$ values. Stable carbon isotope values did show a considerable drop after 1980, as well as some decadal-scale changes in interannual variance throughout the record.

*Coral Growth:* Fig. 7 shows the data on skeletal growth characteristics from the Crocker Reef core. Interannual growth varied much more than the $\delta^{18}O$ data, indicating that factors other than temperature alone were likely to have influenced coral growth. Normally, studies using growth parameters consider data from multiple corals to separate local factors out from broader scale environmental influences. Further work will use skeletal growth from multiple cores at each of multiple sites along the Florida Keys to better understand the full range of environmental conditions that the corals have experienced.

**Discussion**

While the HadISST and Reynolds gridded datasets provide global coverage and long records (HadISST data are available since 1870), they have inherent limitations. Spatial resolution of each is 1°x1° and were based on data from surface ships, with data prior to 1940 were somewhat suspect due to sparse data and problems with source data (Barton et al. this volume). These data are also primarily from major shipping routes, with most data near the Florida Keys coming from the Florida Current. C-MAN/SEAKEYS data also differed from the Hudson loggers and the paleodata in that they were taken near the surface, 32 km (SMKF1) or 18 km (MLRF1) from the reefs.

Comparison of the paleodata with instrumental records showed interesting patterns, especially in terms of the biases. Most of these were consistent with differences in the way each instrumental data set was developed. Most importantly, it was clear that sampling resolution of at least the 12 samples per year used here are necessary for future work. Because of variability at the sites, higher resolution would be preferable, but this would increase project costs. Because the paleodata sample subsurface temperatures where the corals live, and can be extended further back in time, they provide a better source of temperature data for coral reefs than surface-based global reconstructions.

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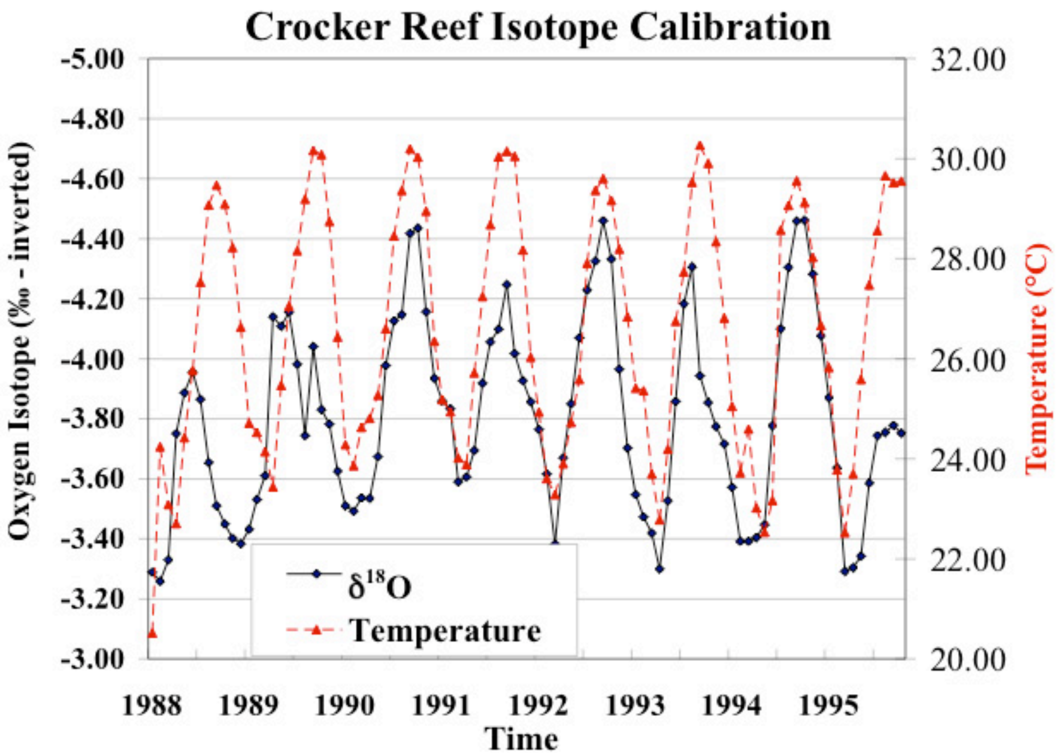


Fig. 5. Comparison of stable oxygen isotope data from the Crocker Reef core with ocean temperature data from the C-MAN/SEAKEYS data from Molasses Reef (correlation $r^2 = 0.44$).

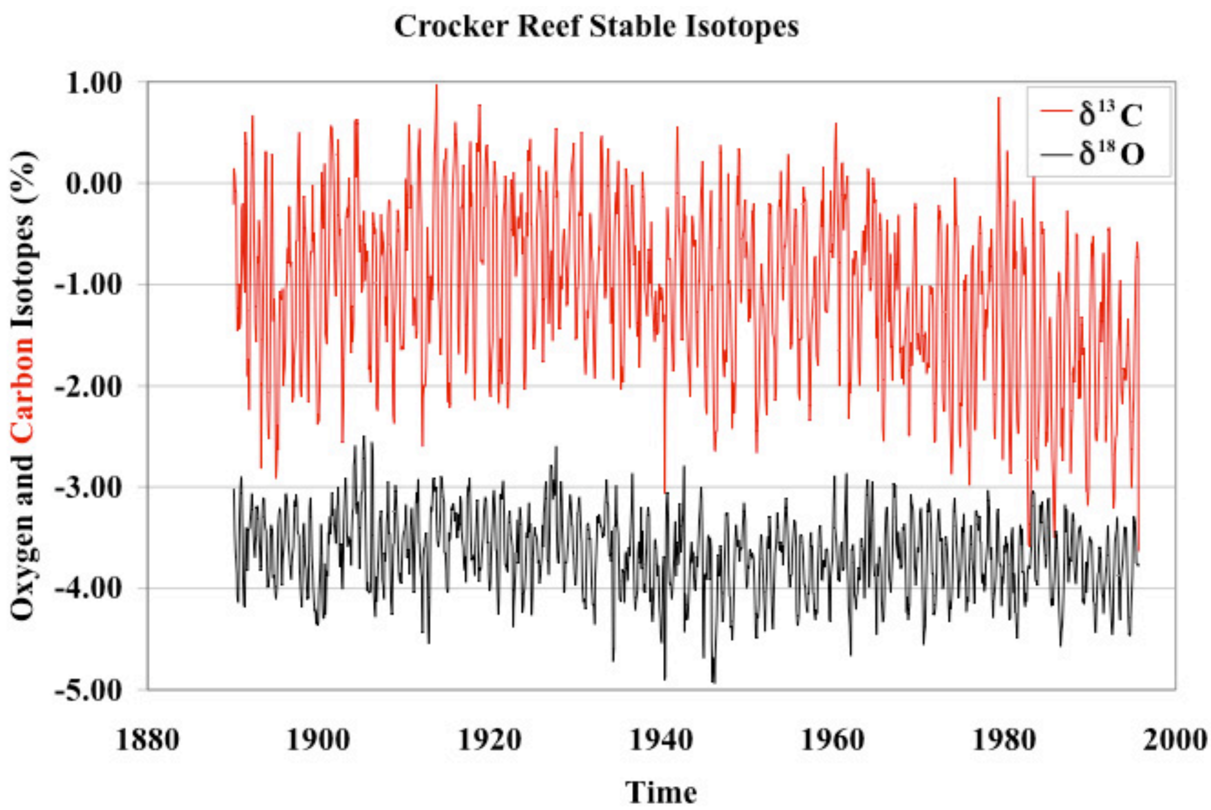


Fig. 6. Data on the stable isotopes of carbon (top) and oxygen (bottom) ($\delta^{18}O$ and $\delta^{13}C$) from the Crocker Reef core. Data were analyzed at an interval of 12 samples per year.

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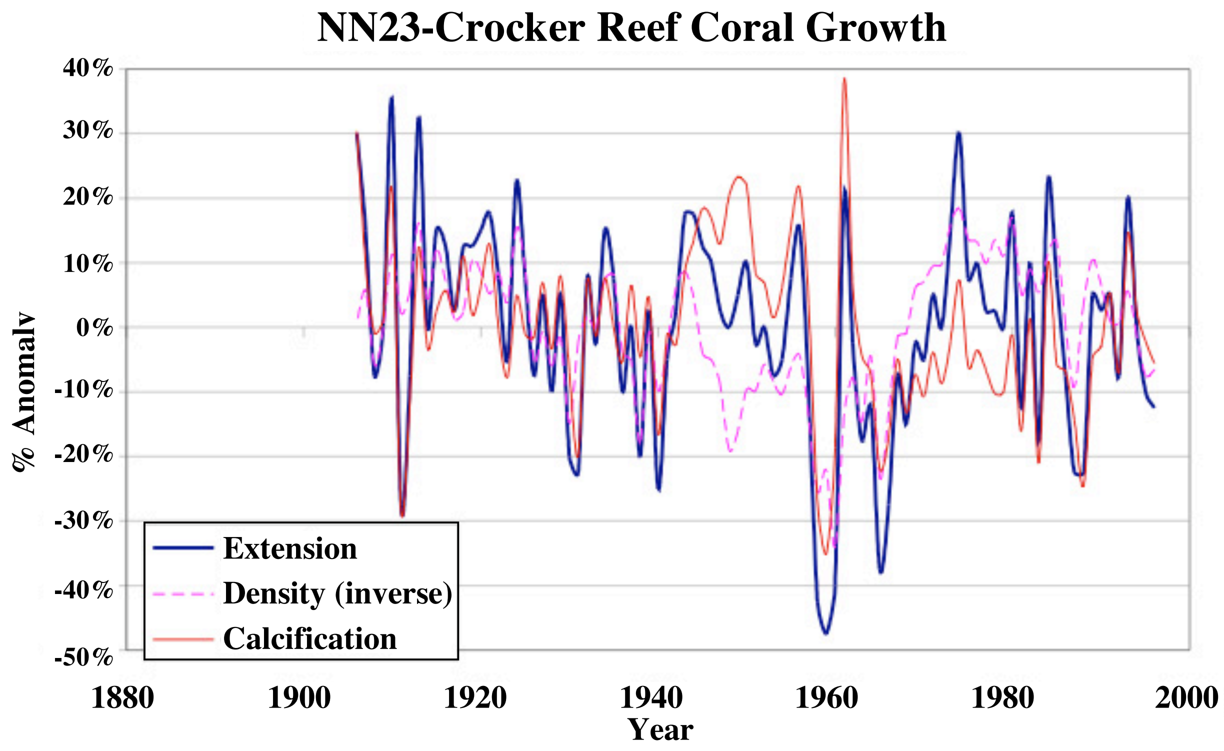


Fig. 7. Data on the annual skeletal growth characteristics from the Crocker Reef core. Percent anomaly calculated as the percent difference between annual growth and the 90-year mean.

This study has begun the process of developing the paleoenvironmental indicators of stress to which corals have been exposed in the Florida Keys. Since the major increase in observations of coral bleaching in the 1980s, managers have been concerned about the impact that this phenomenon may have on coral reefs in the area. These data generated through Coral Reef Watch-Paleo will help us understand if the thermal stress that corals are experiencing in recent decades is unusual or if this is part of a long-term natural cycle. The responses of managers would likely be different depending on the nature of the problem. If this is a normal level of thermal stress, then why are the corals bleaching now? Are other forms of stress contributing to today's bleaching? Managers need to know the frequency of high temperature stress to decide among potential strategies, such as those being developed in a joint NOAA-Great Barrier Reef Marine Park Authority document "Responding to global change: A Reef Manager's Guide to Coral Bleaching" (NOAA in press).

Carbon isotopes have been associated with changes in light intensity reaching the coral (Fairbanks and Dodge 1979), but the interpretation of $\delta^{13}C$ values is still a matter of speculation (Grottoli and Wellington 1999; McConnaughey 1987 a, b; Swart et al. 1996). The decline in $\delta^{13}C$ since the 1900s was probably related to the so-called $^{13}C$ Suess effect (Druffel and Benavides 1986) although relationship to a decline in water clarity that has been reported over recent decades in the Florida Keys (Causey pers. comm.) cannot be ruled out.

In the Sr/Ca data from Looe Key and the stable oxygen isotopic data from Crocker Reef, the relationships with temperatures were significantly different from those previously quoted (Leder et al. 1996; Swart et al. 2002). We believe that these differences in the slopes relate to the resolution at which the corals were sampled (10-12 samples per year). This interpretation supports previously conclusions (Leder et al. 1996) that sampling densities in excess of the theoretical number are necessary to obtain the true temperature resolution, especially in regions that exhibit temperature ranges in excess of 8-10°C.

On a decadal scale, the oxygen isotopic data from the Crocker Reef core showed little change over the length of the record that could be attributed to a long-term temperature trends such as anthropogenic climate change. However it is widely recognized that the oxygen isotopic composition of coral skeletons is influenced by both temperature and the $\delta^{18}O$ of the seawater – the latter being related to salinity. The absence of long term decreases in the $\delta^{18}O$ might be compensated over the same time period by slight increases in salinity. The presence of a salinity effect can be confirmed by using the Sr/Ca ratio (Le Bec et al. 2000; Quinn and Sampson 2002; Rohling and Bigg 1998; Swart et al. 1999; Swart et al. 1998; McCulloch et al. 1994). However, the slope of the Sr/Ca data over time from Looe Key was near zero indicating that there were no long-term changes in SST at that site either. The presence of some decadal scale variability in the Looe Key record suggests that the record from longer cores now being analyzed may provide useful information about low frequency temperature variability. As none of these records extended prior to the pre-20th century, it was not yet possible to determine if the postulated changes in temperature reported for Puerto Rico by Winter et al. (2000) also occurred in the Florida Keys. Additionally, the Winter et al. (2000) record was based on $\delta^{18}O$ that is influenced by temperature, salinity, and water source as discussed above. The Coral Reef Watch-Paleo project is developing sclerochronological, $\delta^{18}O$, and Sr/Ca records using longer cores from the Florida Keys and the Dry Tortugas, as well as continuous multi-century records from Puerto Rico using the cores from the Winter et al. (2000) study and new cores recently collected from a nearby site in Puerto Rico and the U.S. Virgin Islands. Anticipated multi-century records from these locations should help to resolve the question of whether 20th century water temperatures differ significantly from earlier centuries and will provide a regional perspective on pre-instrumental climatic variability.

All data from this work are archived for public access at NOAA's World Data Center for Paleoclimatology (NCDC 2005) and NOAA's Coral Reef Information System (CoRIS 2005).

## Conclusions

This work reported the first result of a NOAA effort focused on developing paleoclimatic records from coral skeletons in areas of management concern. The data available thus far demonstrated that these records will provide information of value to managers concerned about the health of coral reefs in the Florida Keys. Further work will extend these records back in time and expand on the data types available. Sampling will continue at resolutions of at least 12 samples per year, and higher when practical. Further work will also expand this study to more areas in the greater Caribbean region and the Pacific Ocean.


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