ELSEVIER

Palaeogeography, Palaeoclimatology, Palaeoecology 123 (1996) 219–237

PALAEO GEOGRAPHY CLIMATOLOGY ECOLOGY

The stable oxygen and carbon isotopic record from a coral growing in Florida Bay: a 160 year record of climatic and anthropogenic influence

Peter K. Swart [a], Genevieve F. Healy [a], Richard E. Dodge [b], Philip Kramer [a], J. Harold Hudson [c], Robert B. Halley [d], Michael B. Robblee [e]

[a] *MGG/RSMAS, University of Miami, 4600 Rickenbacker Causeway, Miami FL 33149, USA*
[b] *Nova Southeastern University, Oceanographic Center, 8000 North Ocean Dr., Dania FL 33004, USA*
[c] *NOAA/FKNMS, P.O. Box 1083, Key Largo FL 33149, USA*
[d] *U.S.G.S., 600 4th St. S., St Petersburg, FL 33705. Petersburg, USA*
[e] *National Biological Survey, Florida International University, University Park, Miami FL 33199, USA*

Received 4 October 1994; revised and accepted 25 August 1995

Abstract

A 160 year record of skeletal $\delta^{13}C$ and $\delta^{18}O$ was examined in a specimen of the coral *Solenastrea bournoni* growing in Florida Bay. Variations in the $\delta^{18}O$ of the skeleton can be correlated to changes in salinity while changes in the $\delta^{13}C$ reflect cycling of organic material within the Bay. Based on the correlation between salinity and skeletal $\delta^{18}O$, we have concluded that there has been no long term increase in salinity in this area of Florida Bay over the past 160 years. Using salinity correlations between the various basins obtained from instrumental data, we have been able to extend our interpretations to other parts of Florida Bay reaching similar conclusions. In contrast to current ideas which have focused on changes in Florida Bay water quality over the past 20-yr history of the Bay as causative in its decline, we have determined that changes in water quality in this basin were already set in motion between 1905 and 1912 by the construction of the Florida East Coast Railway from Miami to Key West. The construction of the railway resulted in the restriction of the exchange of water between the Florida reef tract and the Gulf of Mexico causing Florida Bay to become more eutrophic. Evidence of this process is observed in the sudden shift to relatively lower $\delta^{13}C$ values coincident with railway construction. Natural events also appear to have influenced the water in the Bay. Between 1912 and 1948 frequent hurricanes had the effect of increasing exchange of water between the Bay and reef tract and removing large quantities of organic rich sediments. However, since 1948 the number of hurricanes affecting the area has decreased and the products of the oxidation of organic material have been increasingly retained within the basin promoting the initiation of eutrophic conditions.

1. Introduction

There has recently been significant interest in determining the history of salinity and water quality in Florida Bay (McIvor et al., 1994 and others). In particular, speculation has focussed on whether events such as the construction of canals to drain the Everglades have adversely affected water quality in Florida Bay. It is suggested that elevated salinities, particularly over the past decade are the principal causative factor in promoting a decrease in water quality, productivity, and biodiversity of

SSDI 0031-0182(95)00078-X

its living resources. Since 1987, large areas of sea grass die-off have occurred in more than 18% of the Bay, blooms of microscopic algae have occurred with increasing frequency and intensity and populations of water birds, juvenile fish, and pink shrimp have declined dramatically (Boesch et al., 1993).

This paper reports on the $\delta^{13}C$ and $\delta^{18}O$ values measured in a core taken from a specimen of the coral *Solenastrea bournoni* which was found growing in an area of Florida Bay known as Lignumvitae Basin in 1986. These data have been used to make interpretations regarding changes in salinity and water quality within Florida Bay prior to anthropogenic change. Interpretations resulting from this study may contribute to future water management decisions which focus on the amounts and timing of freshwater input into Florida Bay.

1.1. Background

Florida Bay is a semi-enclosed basin bordered to the north by the southern tip of peninsular Florida and to the south by the Pleistocene aged Florida Keys (Fig. 1). The water depth of the Bay increases from less than 1 m in the east to more than 3 m in the west, a change which reflects the topography of the underlying Miami limestone. Within the Bay are 237 mud islands, all of Holocene age, interlinked by a series of shallow

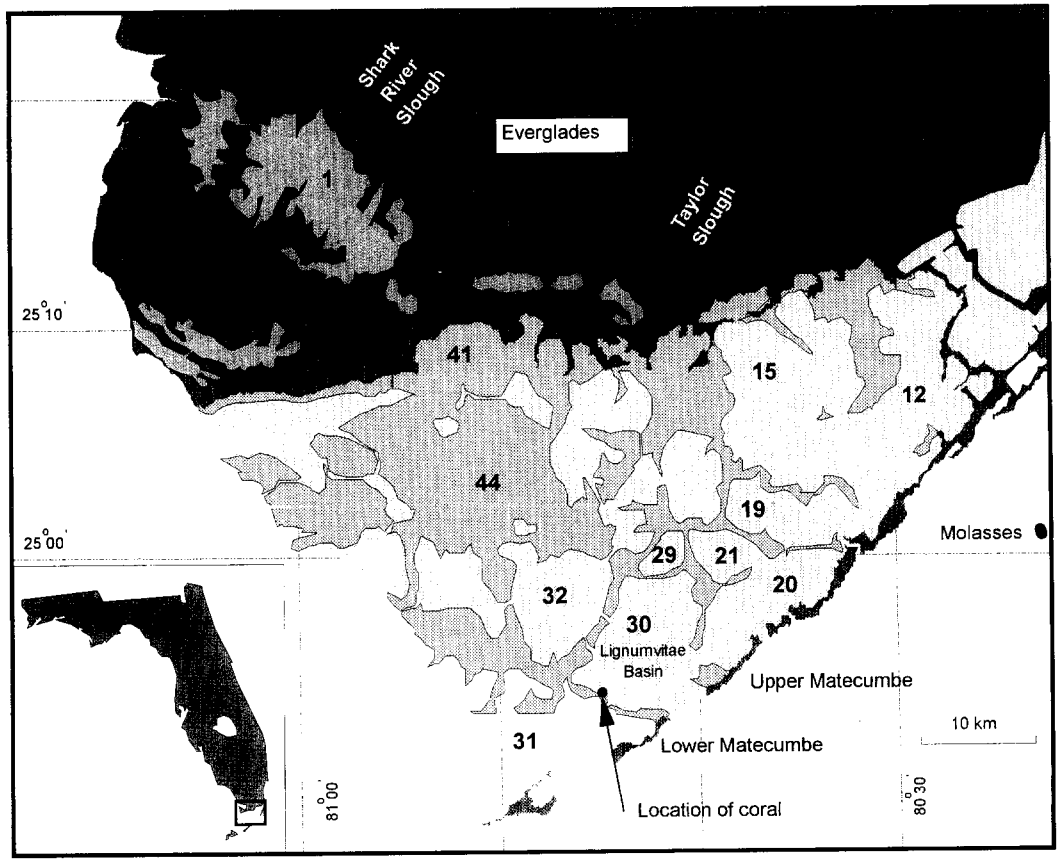

Fig. 1. Location map of Florida Bay showing general location and the division into a series of basins. These basins have been defined numbers by the Everglades National Park and those relevant to this study are indicated. The basins are generally delineated by the presence of mudbanks (shown as a light stippled pattern). Basins discussed in the text are Whitewater Bay (#1), northeast Florida Bay (#15), and Lignumvitae Basin (#30).

mudbanks which have the effect of separating the Bay into basins. Florida Bay water is derived from the intrusion of oceanic water from the Florida Reef Tract and the Gulf of Mexico, local precipitation, and freshwater flow from Shark River Slough, Taylor Slough, and the C-111 canal (Fig. 1). These sources, combined with intense evaporation, result in a body of water with highly variable salinities (Fig. 2a,b).

The specimen of the coral *Solenastrea bournoni*, which is the subject of this paper, was collected from Lignumvitae Basin just to the north of Lignumvitae Key and to the east of the Peterson Keys. Although this basin is situated near to the

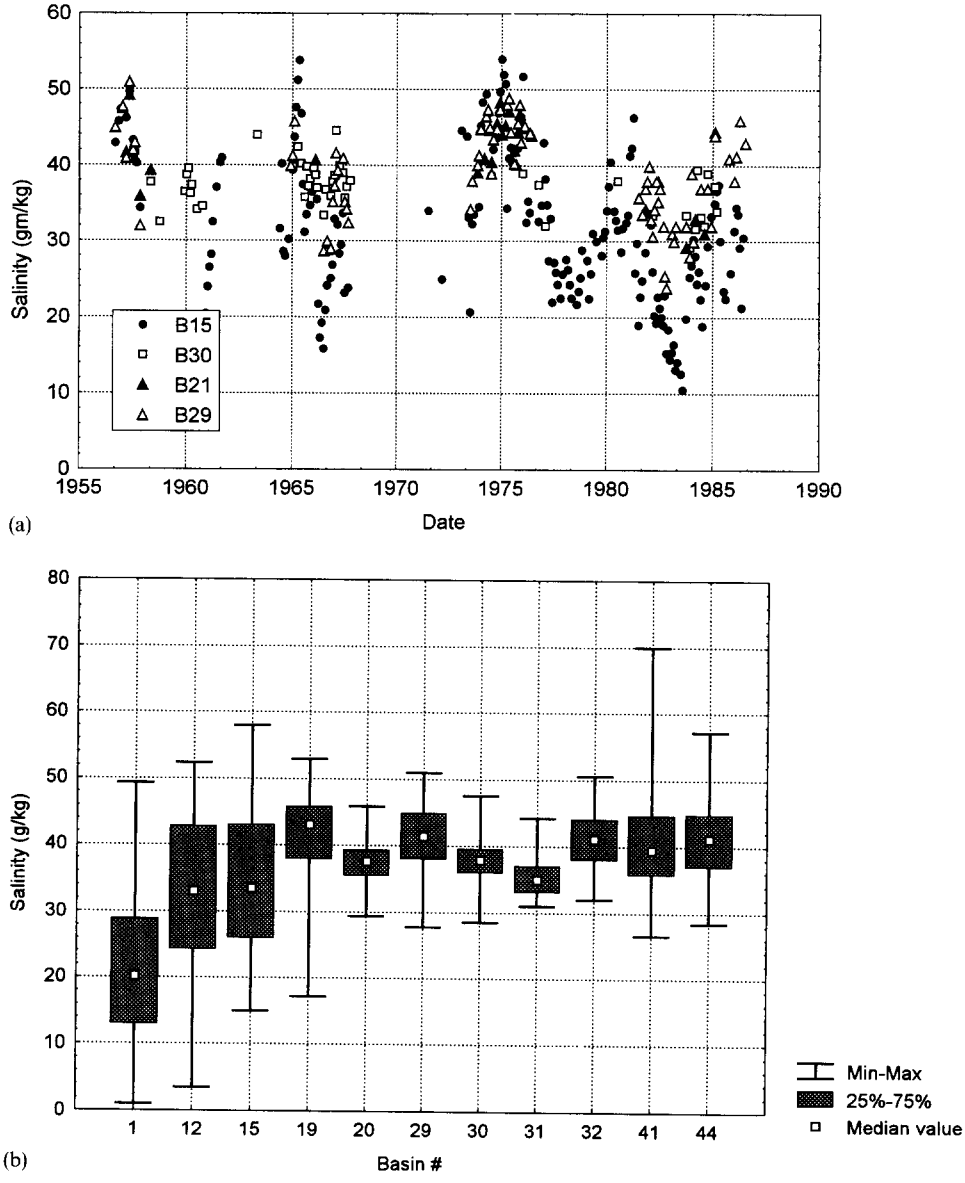

Fig. 2. A. Time series salinity data available for this study from several of the numbered basins shown in Fig. 1 for which more continuous data are available. B. Range of salinities for different numbered basins shown in Fig. 1.

Florida Keys, it still experiences high salinities (Fig. 2a,b).

Temperature and salinity data

Temperature and salinity data for Florida Bay were collected as early as 1946, however, the quantity of data are sparse and discontinuous. Robblee et al. (1989) collected these data together and subdivided them on the basis of date and basin of collection. Some of the basins relevant to this study are shown in Fig. 1. These data show that the range of salinity within Florida Bay is highly variable (Fig. 2b) extending from as low as 2 g/kg in basin 12 to 70 g/kg in basin 41. Inter-annual variations in salinity are typically greater than intra-annual variations (Fig. 3). Generally, the salinity in one basin can be correlated with the salinity in other basins in the Bay (Fig. 4), although the slopes of these relationships vary. From these correlations we have been able to develop equations which allow the salinities of different basins to be calculated from the salinity in Linumvitae Basin on both a daily and monthly basis. Statistically significant correlations were present between salinities in most basins using both daily and monthly datasets, however, higher correlation coefficients were obtained using daily data. For example, Fig. 4 shows the correlation between monthly average salinity values for basins 15, 21, 29, 30, 31, and 32 between 1956 and 1986. In contrast, a correlation between Lignumvitae Basin (basin 30) and northeast Florida Bay (basin 15) based on daily data has a greater statistical significance (Fig. 5).

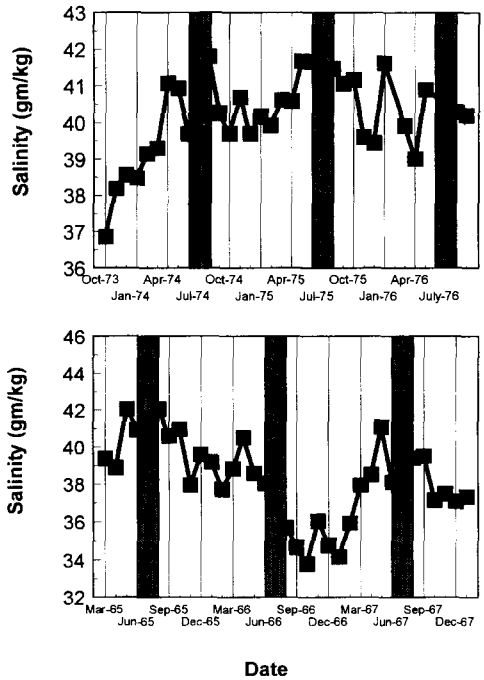

Fig. 3. Monthly average salinity data for basin 30 for two time periods between October 1973 to August 1976 and March 1965 to January 1968. The dark bar denotes the time from June to August of each year, usually the time of the warmest temperatures and highest salinities.

Previous work on Solenastrea bournoni

The coral analyzed in this study was cored in 1986. At that time, two colonies of *Solenastrea bournoni* (FB-5 and FB-6) within Lignumvitae basin were drilled. The growth and fluorescence of one of these, FB-5, was described in papers by Hudson et al. (1989) and Smith et al. (1989). Hudson et al. (1989) reported an average growth rate of 8.95 mm a year for this coral, but noted below average growth coincident with railway construction between 1905 and 1912. They were, however, unable to correlate abnormally cold air temperatures, hurricanes, or dredging activity with growth rate changes.

The second paper, by Smith et al. (1989), reported on the fluorescent characteristics of the coral skeleton. They reported a marked decrease in the fluorescence of the coral skeleton after 1940, which they interpreted as being the result of a reduction in the discharge of freshwater from the Everglades through Shark River Slough. Smith et al. also noticed a loss in the characteristic 4–6 yr rainfall frequency in the fluorescence data after 1932 which they concluded supported their interpretation of the reduction in freshwater flow through Shark River Slough.

This paper reports on the $\delta^{13}C$ and $\delta^{18}O$ values of FB-6, which has interpretable density banding patterns between 1824 and 1986.

2. Methods

Coring: The coral used in this study was cored in 1986 using the techniques described by Hudson et al. (1989).

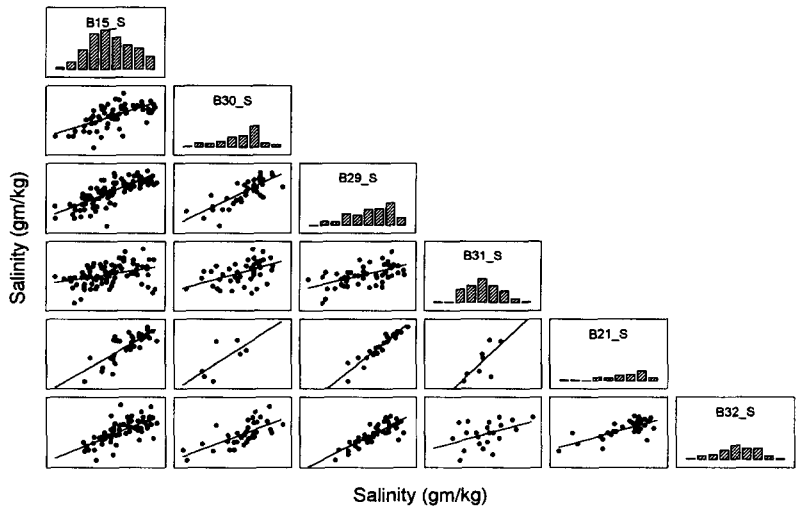

Fig. 4. Correlation of salinity data between various basins using average monthly salinity between 1956 and 1986. For basin numbers see Fig. 1.

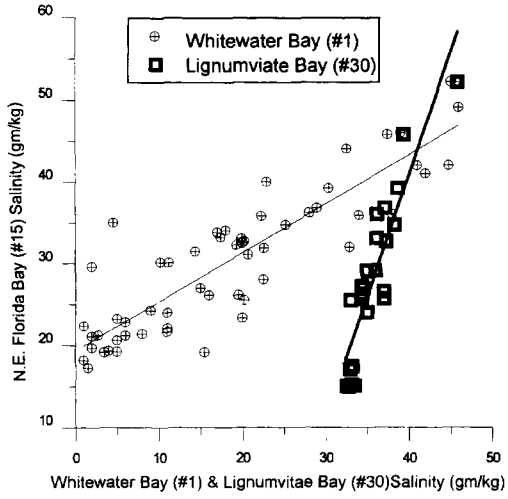

Fig. 5. Detailed correlation between salinity in Lignumvitae Basin (basin 30, northeast Florida Bay (basin 15) and Whitewater Bay (Basin 1). Correlations based on daily data between 1956 and 1986.

X-ray densitometry: The core was slabbed and subjected to X-radiography using standard methods (Dodge et al., 1984; Hudson et al., 1981a,b).

Isotope analyses: Samples for isotopic analyses were drilled using a small diamond studded dental drill combined with an XYZ stage. Between 3 and 12 samples were drilled in one year depending on the growth rate of the coral. The coral was sampled as far as possible along continuous polyp tracts. These are marked on Fig. 6. The record is complete with the exception of three years (1833–1836) where the samples were lost as a result of an equipment malfunction. The samples were analyzed for their $\delta^{13}C$ and $\delta^{18}O$ values using standard methods (Swart et al., 1991). All data have been corrected for the usual isobaric interferences.

Statistical techniques: In order to perform time series analyses, data were interpolated to a common time interval using the method derived from Davis (1973). Time series analyses were performed using Statistica (Statsoft©) and single spectral analysis was performed using a program provided by Ed Cook (LDGO).

3. Results

3.1. Growth rate

The growth rate of the coral (FB-5) originally studied by Hudson et al. (1989) was highly variable, exhibiting variations between 4.4 and 15.2 mm/yr. In contrast, the coral (FB-6) examined in this study exhibited lower, (mean = 5.07 mm/yr), but generally more uniform rates of growth. Nevertheless, the growth rate of FB-6 is

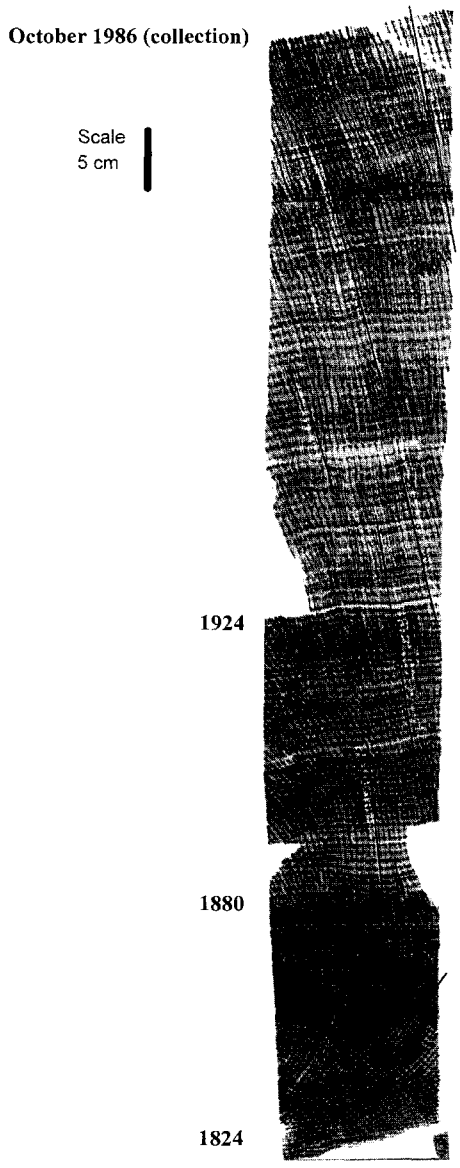

Fig. 6. X-radiograph of the coral used in the study.

punctuated by two sudden increases in growth rate, in 1883 and 1924 (Fig. 7). The growth rate of FB-6 showed no correlation with that of FB-5.

3.2. Stable isotopes

Oxygen

The $\delta^{18}O$ of the coral skeleton has a mean value of −2.58‰, and varies between −0.77 and −5.76‰. The average annual variation is 1.21‰, but this range varies between as little as 0.17‰ to as great as 4.42‰. The average $\delta^{18}O$ is higher by approximately 0.7‰ compared to corals of the same species growing off the Florida coast (Fig. 8). There is no long term trend in the skeletal $\delta^{18}O$, although the values tend to be less variable and the average annual $\delta^{18}O$ increases from −2.75 to −2.44‰ after 1910 (Fig. 9).

Carbon

The $\delta^{13}C$ of the coral skeleton has a mean value of −3.18‰ and varies between −1.10 and −5.20‰. The average annual range of $\delta^{13}C$ is 0.98‰, and varies between 0.15 and 2.66‰. The average $\delta^{13}C$ of this coral is approximately 0.5‰ lower than a specimen of the same genus growing off the Florida coast (Fig. 8) and considerably lower than specimens of *Montastraea annularis* found on the reef tract. There are two major decreases in the skeletal $\delta^{13}C$, one around 1905 and one starting in 1948 (Fig. 9).

3.3. Fourier analysis

A spectral analysis of annual mean $\delta^{18}O$ values, shows statistically significant peaks at 7, 12, 25, and 43 yr (Fig. 10). Statistically significant peaks are present in the $\delta^{13}C$ spectra at 12, 25 and 100 yr. Cross spectral analysis indicates that signals at 12, 20–25, and 80–100 may be common to both the $\delta^{13}C$ and $\delta^{18}O$ records. Single spectral analysis of the $\delta^{18}O$ data indicates temporal variability of all the frequencies, with perhaps the most significant decrease taking place in the amplitude of the 7-yr signal between 1880 and 1920 (Fig. 11a).

4. Discussion

4.1. Density banding

In massive corals, a complete cycle of high and low density skeleton is believed to form annually (Knutson et al., 1972; Dodge and Thompson, 1974; Hudson et al., 1976; Wellington and Glynn, 1983). Through these growth increments, the coral skeleton contains a chronology of annual growth

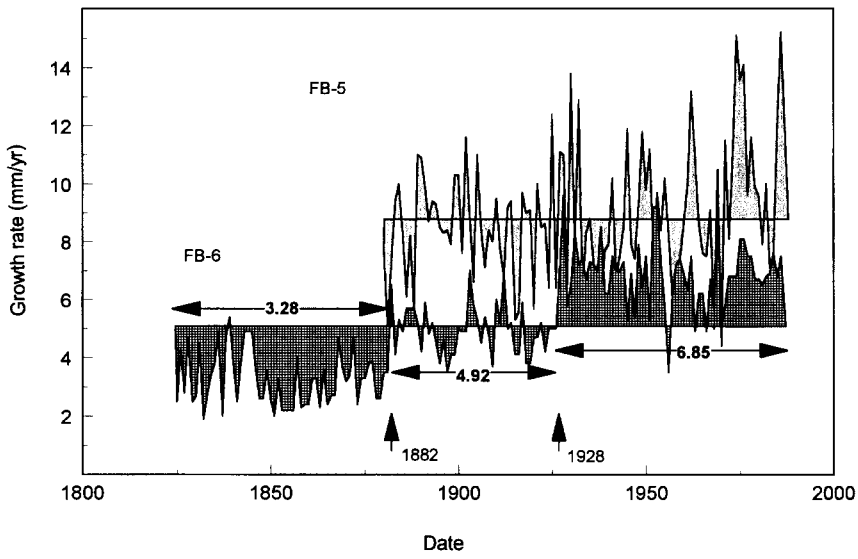

Fig. 7. Time series of growth rate data reported in Hudson et al. (1988) on coral FB-5 and in this paper (FB-6).

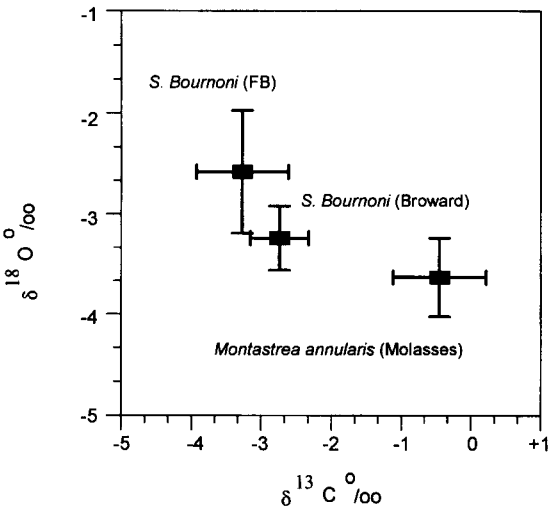

Fig. 8. Comparison of $\delta^{13}C$ and $\delta^{18}O$ data from *Solenastrea bournoni* ($n=1153$) compared to a specimen of *Montastraea annularis* ($n=300$) growing on Molasses reef (Fig. 1) and a specimen of *Solenastrea bournoni* ($n=28$) collected from Broward county, approximately 100 miles to the north of Molasses. The Florida Bay coral has a statistically higher $\delta^{18}O$ and lower $\delta^{13}C$ composition than the coral from Broward county.

variations. In South Florida, the dense band forms in the late summer, but it is generally thought that there is as much as a $\pm$ two month variation in timing. By counting the number of bands in a coral, the age can be assessed. Errors in age interpretation arise when dense bands are indistinct or when so-called "stress bands", resulting from events such as temperature extremes, occur. Generally speaking, a year in which a stress band forms may actually contain two dense bands or a thicker dense band which is a combination of the stress and normal dense band. Although it is possible to misinterpret a stress band as an annual band, the annual bands can be recognized by their regular spacing. Therefore, density changes can still provide a clear annual chronology. We feel reasonably confident that the density bands in this coral do represent an annual phenomenon. If dense bands are misinterpreted as annual bands, one can expect the measured growth rate to show large variations between years. This is not the case in this coral with the exception of two years, 1954 and 1969. In these years, the coral exhibited a high growth rate followed the next year by a low extension rate. It is possible that there was a misidentification of the stress and an annual band coupled with a missing annual dense band, however, the error was accommodated the following year. Hence over the life of the coral such errors cancel each other out. In conclusion, while there

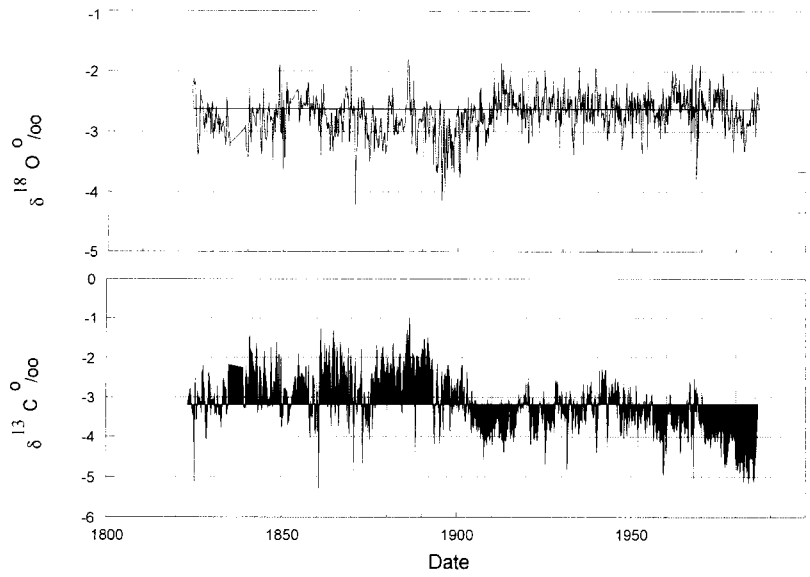

Fig. 9. The $\delta^{13}C$ and $\delta^{18}O$ data described in the text. The shading indicates deviations from the mean value.

may be some uncertainty as to the age within one or two years, this uncertainty does not alter the age of the coral significantly.

4.2. Oxygen isotopes

The average $\delta^{18}O$ of the skeleton ($m = -2.57$; $n = 1153$) is markedly higher than corals growing in normal marine environments and a specimen of the same species growing on the Florida reef tract (Fig. 8). The higher skeletal $\delta^{18}O$ value reflects the high $\delta^{18}O$ value of the Bay water itself (Lloyd, 1964; Swart et al., 1989), which is enriched in ^{18}O as a result of evaporation and the input of ^{18}O enriched freshwater from the Everglades (Meyers et al., 1993).

Inter-annual variations

Using measured temperature variations in Lignumvitae basin over the time period between 1956 and 1992 (14–32°C), we have been unable to find any correlation between $\delta^{18}O$ and temperature (Fig. 12b). In addition, based on previous relationships between temperature and $\delta^{18}O$ in corals (Weber and Woodhead, 1972), the average annual range in $\delta^{18}O$ in the coral skeleton corresponds to less than 50% of what might be expected on the basis of the annual monthly range in water temperature of approximately 10°C; assuming constant $\delta^{18}O$ of the water. As discussed by Leder et al. (1991), possible explanations for this reduced range, include an insufficient number of samples taken within one year, and changes in the $\delta^{18}O$ of the water linked to variations in evaporation and terrestrial runoff.

Number of samples

It has been recognized by Leder et al. (1992, 1994, in press), that both the number of samples taken within one year and the location of these samples within the coral skeleton can significantly alter the range of isotopic compositions measured within an annual growth increment. Our sampling regime produces an average of the isotopic composition of the skeleton over a period of several months, integrating variations in temperature, physiological effects, and the isotopic composition of the water. As a result, we are unable to attach any significance to the annual range of either the $\delta^{13}C$ or $\delta^{18}O$ in the skeleton.

Salinity variations

Although there have been no systematic studies of the $\delta^{18}O$ of the water within Florida Bay, the

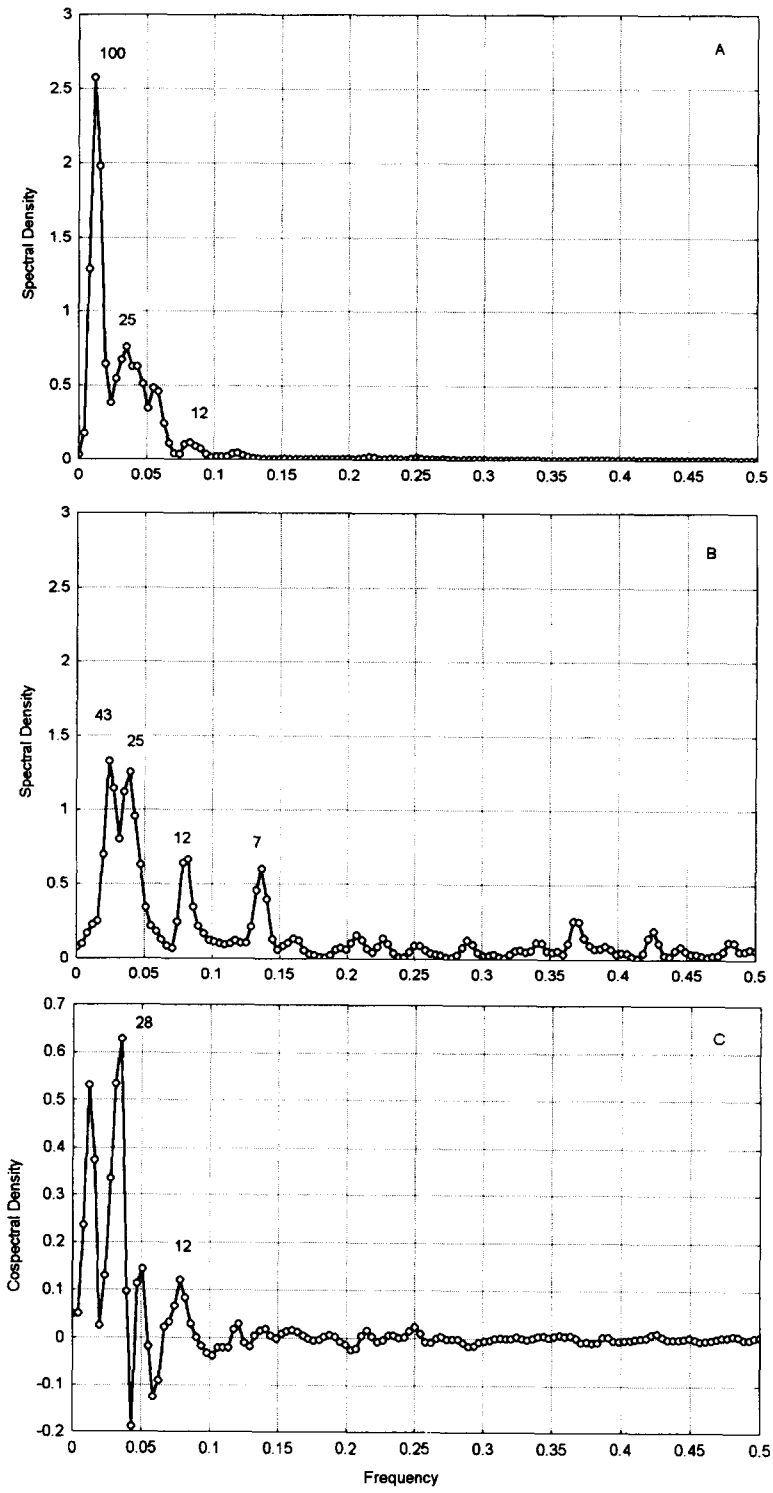

Fig. 10. A. Spectral analysis of the mean annual $\delta^{18}O$ values. B. Spectral analysis of the mean annual $\delta^{13}C$ values. C. Cross-spectral analysis of the $\delta^{13}C$ and $\delta^{18}O$ annual mean data sets. Statistically significant peaks are marked.

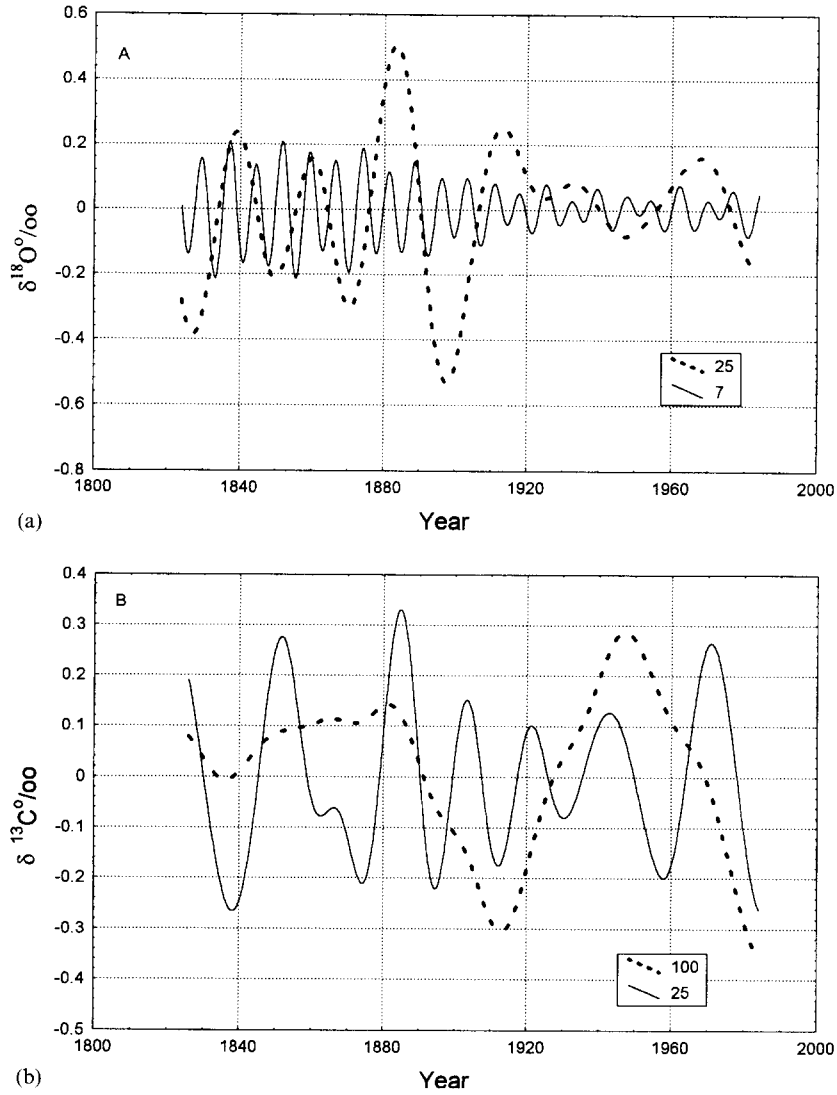

Fig. 11. Single spectral analysis of important spectral components shown in Fig. 10 for oxygen (A) and carbon (B). Single spectral analysis identified the variation of a particular frequency with time.

salinity of the Bay shows both large inter- and intra-annual variations. Typically, salinity values are the highest during the summer, as a result of evaporation, and lower during the winter when the Bay becomes dominated by water from the Gulf of Mexico and the Florida Reef Tract. The absence of clear predictability in salinity can be seen by examining two periods for which there is more or less continuous data from basin 20 (October 1973 to September 1976 and March 1965 to January 1969) (Fig. 3). In both datasets salinity values appear to be higher in the preceding summer than the following winter. Superimposed on the seasonal trend are longer term variations which result in large differences in salinity between successive summers and winters. These changes in salinity should be manifested in the $\delta^{18}O$ of the coral, but as the maximum enrichment in the water occurs during the warmest portion of the year (the summer), the temperature and salinity effects tend

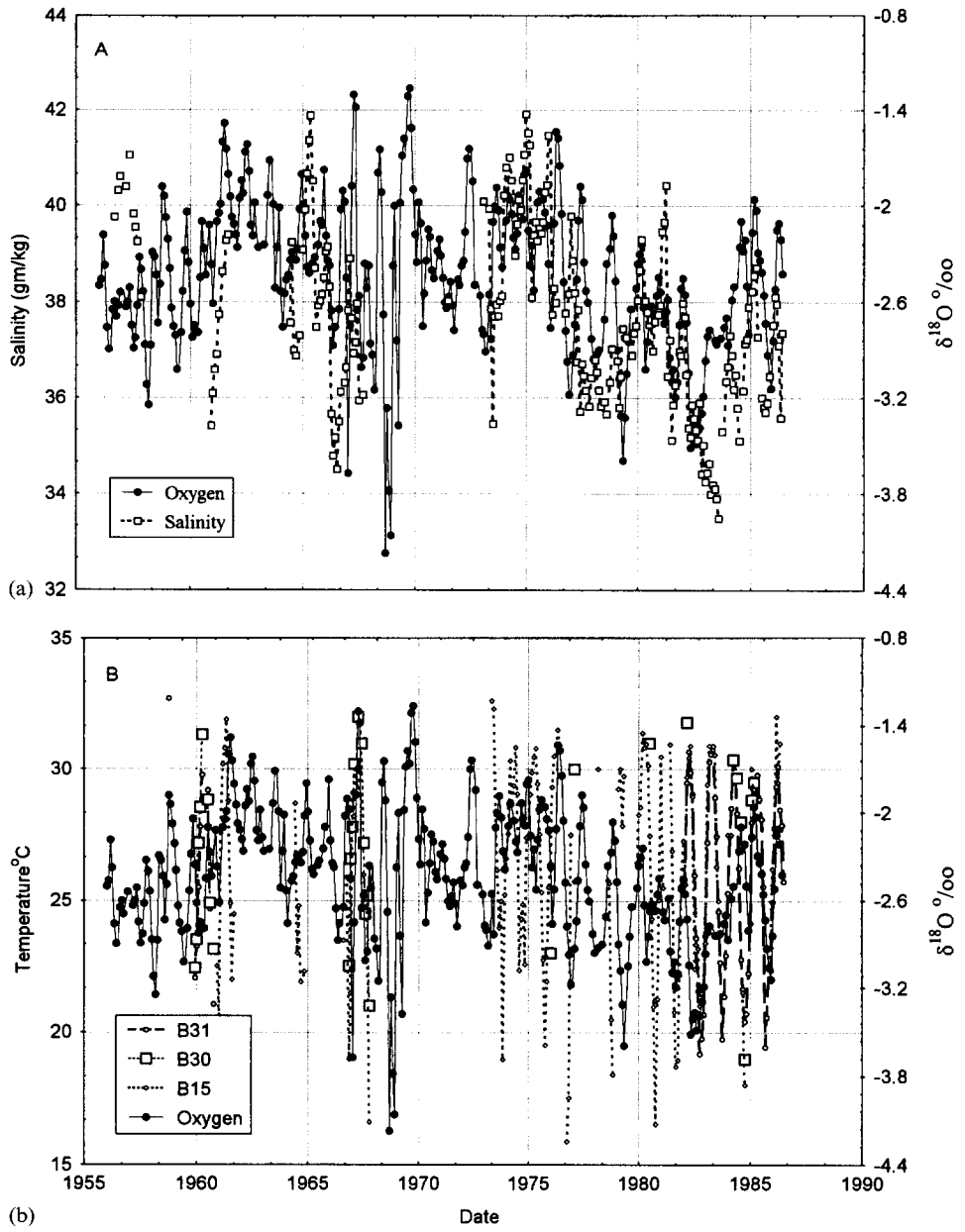

Fig. 12. A. Time series showing the variation in salinity and oxygen isotopic composition for the portions of the record from Lignumvitae basin for which salinity data are available. B. Time series of oxygen isotopic data from the coral together with temperature data from basin 30. The scales have been adjusted so that the ranges of expected oxygen isotopic composition are equivalent to the measured temperature. Note that in some instances there is an inverse relationship with temperature, in other instances there is a positive correlation (See text).

to counteract each other, thereby reducing the observed range of oxygen isotopic variation seen in the coral.

Timing of density band formation

Normally the high density band in Florida corals is believed to form between July and August. This has been determined both by direct observation and the position of the high density band relative to the occurrence of the lowest stable $\delta^{18}O$ value (Emiliani et al., 1978; Leder et al., 1991). In Florida Bay, the dense band also seems to form mainly during the period when the $\delta^{18}O$ value is lowest. However, there are some years when the dense band forms at the time when the skeletal $\delta^{18}O$ is at its highest value within an individual year (Fig. 13). In Fig. 13, the position of the dense band is marked by both the vertical shading and the position of the date. During this portion of the record, from 1966 to 1986, there were five years in which the dense band coincided with the highest $\delta^{18}O$ values. The lack of coincidence of the dense band and the zone of minimum $\delta^{18}O$ values may indicate either that the basin was more saline during the summer in these years, or that the dense band formed at some other time. Such a change in timing need not be by more than a few months in order to shift the dense band into a portion of the skeleton with higher $\delta^{18}O$.

Correlation with temperature and salinity

The salinity and temperature database available for correlation has been discussed earlier. As only a relatively short and discontinuous salinity record was available for basin 30, we have correlated the salinity of basin 30 to that of basin 15 and then used the basin 15 record to reconstruct a longer time series for basin 30. The correlation coefficient between salinity in basin 30 and 15 is 0.61, statistically significant at the >95% confidence level. In

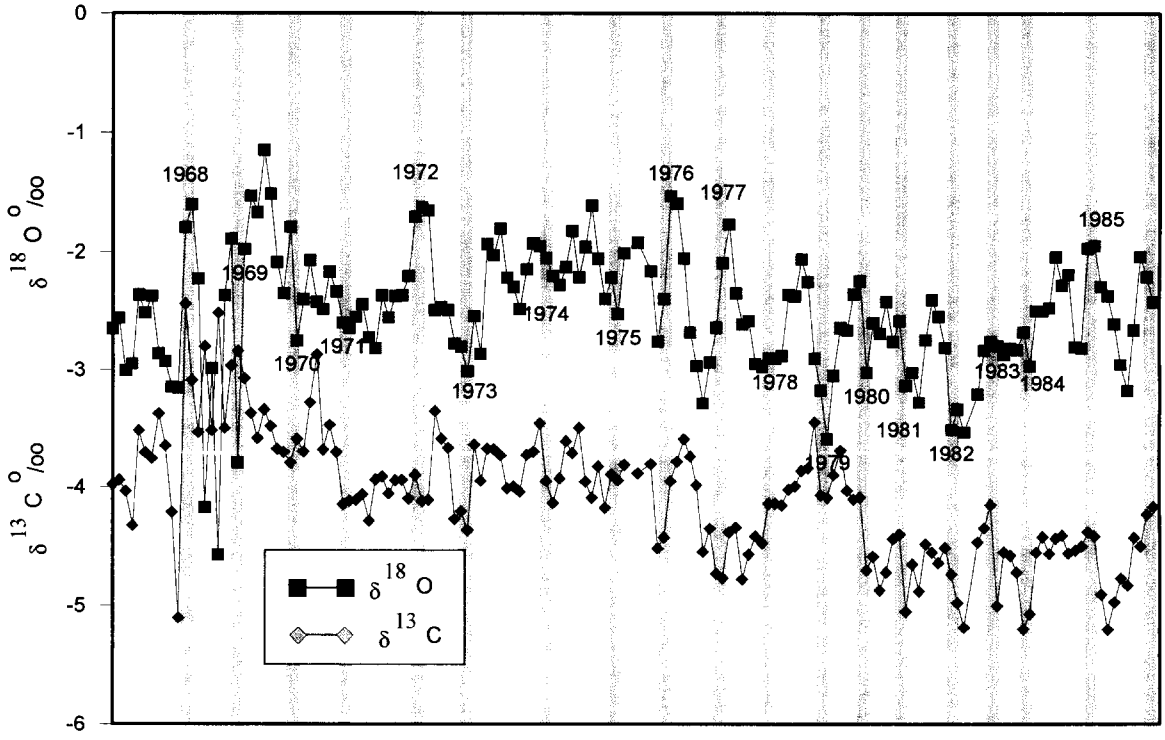

Fig. 13. Time series analysis of $\delta^{13}C$ and $\delta^{18}O$ from 1966 to 1986. In this figure the position of the date is located on the graph where the dense band occurs relative to the oxygen isotope curve. Note there appears to be a depletion in the $\delta^{13}C$ coincident with the density band.

order to correlate these data to the $\delta^{18}O$ of the coral skeleton, we first extrapolated our $\delta^{18}O$ values to 12 samples a year assuming that the density band in the skeleton formed during July. The salinity and temperature data were then correlated with the $\delta^{18}O$ data (Fig. 12a). While a correlation between salinity and skeletal $\delta^{18}O$ (Fig. 14) shows a regression coefficient of 0.41 (statistically significant at >99.99% level), no statistically significant correlation was observed between water temperature and $\delta^{18}O$ ($r=0.08$). The reason for the absence of correlation between skeletal $\delta^{18}O$ and temperature is evident if one examines the available temperature and skeletal $\delta^{18}O$ data. The $\delta^{18}O$ composition of the coral skeleton shows a regular annual variation which is sometimes in phase and some times out of phase with temperature. The variability of the correlation between temperature and $\delta^{18}O$ suggests that either other factors such as salinity are masking the temperature induced isotopic effect in the coral skeleton, or that the chronology based on the density bands is slightly incorrect. The data presented in this paper suggests that while some salinity induced masking is taking place, the main factor resulting in the absent correlation between temperature and $\delta^{18}O$ is the variable timing in the dense band formation. The precise position of the density band is critical in determining the degree of correlation between temperature and $\delta^{18}O$ on an intra-annual scale, and therefore an error of several months can clearly alter the chronology and hence correlation, without affecting the annual age assignment.

In contrast, the correlation between skeletal $\delta^{18}O$ and salinity is much more robust as there is less of an intra-annual signal in salinity and more variability between years. The result is that the $\delta^{18}O$ and the salinity clearly track each other (Fig. 12a). Scatter in this correlation arises from a combination of several processes (Fig. 15). First, some problems can occur in the chronology of the coral as previously discussed and the assumption that growth rate between the bands is constant. Second, while temperature is not directly correlatable with $\delta^{18}O$, it still has an important control on the $\delta^{18}O$ of coral skeletons. At this location, temperature varies in a seasonal manner and while temperature influences the seasonal $\delta^{18}O$ signal, it is not primarily responsible for inter-annual variations in skeletal $\delta^{18}O$ which are in some instances greater than intra-annual changes. If temperature were the most important factor, we believe that the $\delta^{18}O$ value would behave in a more predictable manner relative to the position of the density bands. Third, the relationship between salinity and the $\delta^{18}O$ of the water is not a simple matter of

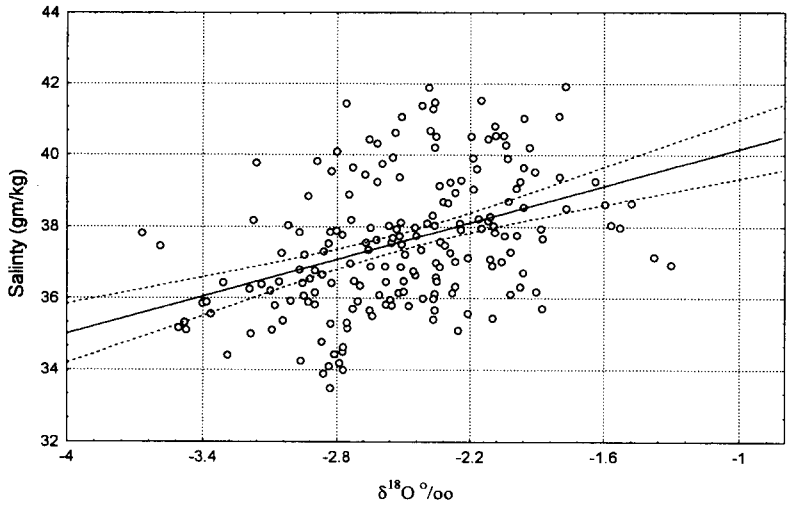

Fig. 14. Correlation between the mean monthly salinity data calculated for Lignumvitae basin (basin 30) and the $\delta^{18}O$ composition of the coral *Solenastrea bournoni*. The overall correlation coefficient is 0.41 for a sample size of 197.

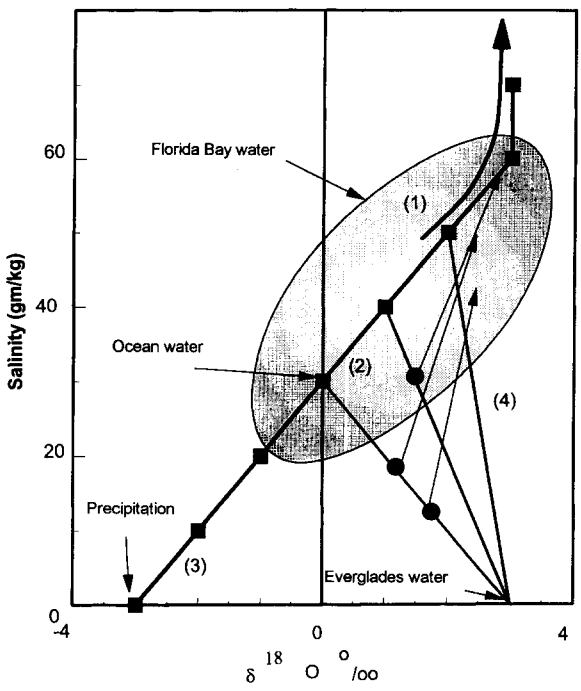

Fig. 15. Model accounting for variation in the oxygen isotopic variation of Florida Bay water. The numbers on the figure refer to the factors accounting for the variation in the oxygen isotopic composition and are discussed in the text. The $\delta^{18}O$ of the water is controlled by mixing between ocean water and precipitation and runoff. Precipitation and runoff while having similar salinities, have quite different $\delta^{18}O$ values. Evaporation of the resultant mixtures increases both the salinity and $\delta^{18}O$ values. The maximum $\delta^{18}O$ composition which can be attained is limited by exchange with the atmosphere.

mixing isotopically depleted freshwater water with seawater. In fact, there are at least four factors important in altering the magnitude and slope of the salinity vs. $\delta^{18}O$ relationship in the waters. These are:

(1) The evaporation of Florida Bay water results in an increase in salinity and to some extent the $\delta^{18}O$ of the Bay water (Lloyd, 1964; Swart et al., 1989). This increase in turn is reflected in the $\delta^{18}O$ value of the coral skeleton. The maximum extent to which the $\delta^{18}O$ of the Bay water can increase is limited by exchange with the atmosphere(Gonfiantini, 1986; Swart et al., 1989). In the case of Florida Bay, the maximum $\delta^{18}O$ of the water that can be attained through evaporation has been calculated by Swart et al. (1989) to be approximately +3‰.

(2) The inundation of Florida Bay water by marine waters from the Gulf of Mexico or the Gulf Stream can act to either reduce or increase the salinity depending upon the salinity and isotopic composition of the Bay at the time of inundation.

(3) Reductions in salinity and $\delta^{18}O$ result from the addition of water through precipitation. The average $\delta^{18}O$ of the precipitation in the Bay is approximately −3‰ (Swart et al., 1989).

(4) Input of water from the Everglades while reducing the salinity, actually can cause an increase in the $\delta^{18}O$. This is because these waters are highly evaporated (Meyers et al., 1993) and have therefore attained the maximum $\delta^{18}O$ possible under the prevailing environmental conditions.

Long term variations in salinity

Based on the correlation between salinity and $\delta^{18}O$ in the coral skeletons (Fig. 9), it is possible to calculate long term variations in salinity in Lignumvitae Basin over the entire record of the coral. Our conclusion is that although there was a slight increase in the $\delta^{18}O$ value of the coral coincident with the construction of the Florida East Coast Railway, there is no overall increase in the $\delta^{18}O$ between 1824 and 1986. Consequently, we conclude that there has been no long term increase in the salinity of Lignumvitae Basin. Similarly, using the correlations between Lignumvitae Basin and other basins (Fig. 4), salinities in these basins can be calculated (Fig. 16). As the correlation coefficient between the salinity and skeletal $\delta^{18}O$ only explains 20% of the variance, the variations in the calculated salinities are not as great as were actually measured. However, this does not alter one of the important findings of this work which is that there has been no long term increase in the salinity of Florida Bay over the past 160 years.

Spectral analysis of oxygen isotopic data

Spectral analysis of the time series of the oxygen isotopic data revealed statistically significant peaks in the spectral density at frequencies corresponding to 7, 12, 25, and 43 years (Figs. 10 and 11). While

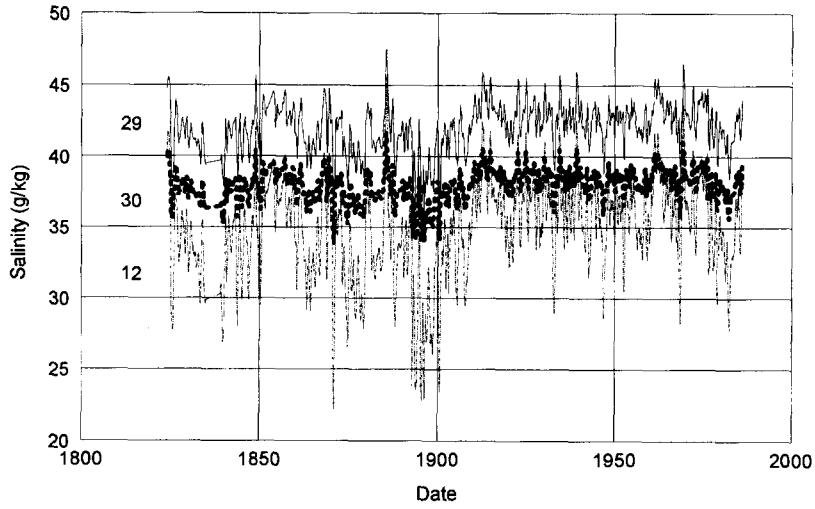

Fig. 16. Calculated salinity variations in Lignumvitae Basin using the $\delta^{18}O$ record shown in Fig. 8. Also shown is the calculated salinity in basin 12 and basin 29 as calculated using the correlations between basins shown in Fig. 5.

single spectral analysis of all of these signals showed variation in amplitude with time, only the 7-yr signal decreased from the start of the record to the present day. The majority of the decrease occurs in a narrow time period between 1880 and 1920, and may be related to the construction of the railway. Smith et al. (1989) observed a change in the periodicity of a 5-yr cycle in fluorescence data prior to and after 1940. The 5-yr frequency is characteristic of rainfall in the South Florida area and therefore Smith et al. concluded that the loss of this signal supported their contention that there had been a decrease in the water flow through the Shark Valley Slough. If variations in the skeletal $\delta^{18}O$ are related to changes in salinity which in turn are related to precipitation and runoff, then it is surprising that no 5-yr signal is present in the isotopic record of the coral. One explanation may be that there is a lag between precipitation in the Everglades and its effect on the salinity in Florida Bay which may last upto 2 years.

Relationship of oxygen isotopic variations to major storms

Throughout the $\delta^{13}C$ and $\delta^{18}O$ record of this coral and particularly in the 20th century, there appears to be a periodicity in the record corresponding to between 7 and 12 yr. These fluctuations from relatively high $\delta^{18}O$ values to lower values often occur during years of major hurricanes. We suggest that the passage of hurricanes causes more ^{18}O-depleted ocean water to influence the Bay resulting in a change in the $\delta^{18}O$ values of the coral skeleton (see discussion on carbon).

4.3. Carbon isotopes

The mean $\delta^{13}C$ of the coral skeleton in this study is lower than corals of the same species growing off Broward county and substantially lower than other species such as *Montastraea annularis* found on the Florida Reef Tract (Fig. 11). This difference is probably a result of the lower $\delta^{13}C$ of the DIC in Florida Bay (Patterson and Walters, 1994). On an intra-annual basis there appears to be a cycle in the $\delta^{13}C$, with lower values coincident with the density band formation during the summer. This annual cyclicity may be linked to either seasonal changes in the $\delta^{13}C$ of the DIC in Bay water, becoming isotopically depleted during the summer months or changes in the rate of respiration relative to photosynthesis in the zooxanthellae (Swart, 1983). Although, low $\delta^{13}C$ values are manifest throughout the skeletal record, a major change toward more lower $\delta^{13}C$ values occurs between 1905 and 1912

coincident with the construction of the railway (Figs. 9 and 17). Between the end of the construction and 1946, there was a slight drift toward higher $\delta^{13}C$ values. Since 1946 the $\delta^{13}C$ values have become lower by at least 1‰. The most plausible cause for the overall negative $\delta^{13}C$ values of this coral, as well as the abrupt shift coincident with the construction of the railway, is that during construction several of the passes through the Keys were infilled reducing exchange of water between Florida Bay and the reef tract. This infilling resulted in more of the products of oxidative decay of organic material (^{13}C depleted carbon, P, and N) being retained within the Bay, producing Bay water with a dissolved inorganic carbon content more depleted in ^{13}C. Subsequent to construction of the railway, the $\delta^{13}C$ of the coral skeleton increased slightly until 1946. Major excursions in the skeletal $\delta^{13}C$, from low to high values and in the $\delta^{18}O$, from high to low values correspond approximately with the occurrence of major hurricanes and storms. These storms had the effect of breaking down the isolation of the Bay, removing large amounts of organic rich sediments and introducing water enriched in ^{13}C from the Florida Reef Tract and the Gulf of Mexico (Fig. 17; Trend A). Between 1910 and 1948, seven class-3 or greater hurricanes passed through Florida Bay. Between 1948 and 1986, the time of the collection of the coral, the $\delta^{13}C$ of the coral gradually became isotopically lighter (Fig. 17; Trend B and D). A reversal in the trend in $\delta^{13}C$ occurred between 1959 and 1966, the only time period since 1948 during which major hurricanes affected Florida Bay (Fig. 17).

One puzzling aspect of the decrease in skeletal $\delta^{13}C$ is the absence of a corresponding increase in the $\delta^{18}O$ over the same period. There are two possible explanations for the absence of a similar trend in $\delta^{18}O$. First, the $\delta^{18}O$ of water in the Bay

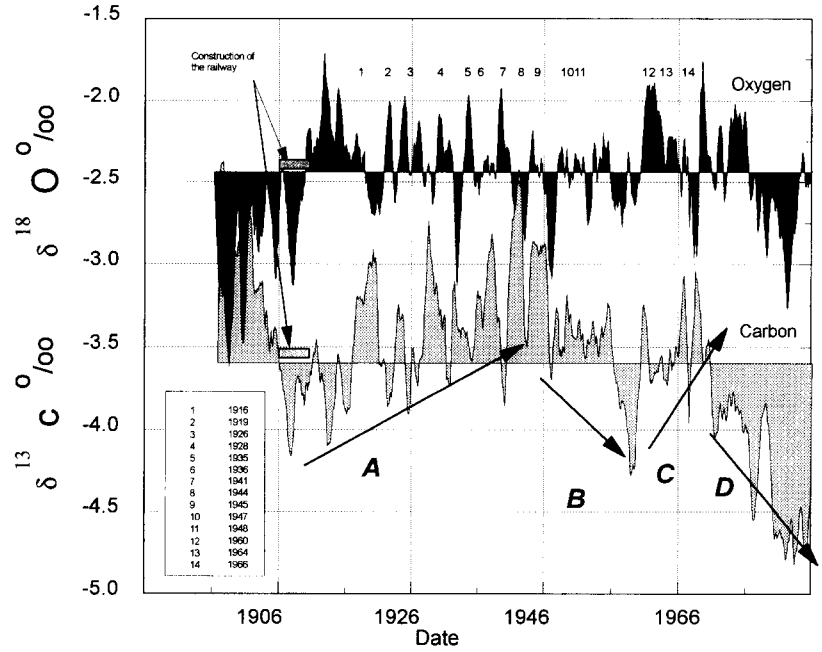

Fig. 17. The $\delta^{13}C$ and $\delta^{18}O$ composition of the coral since 1900 showing the timing of major hurricanes. Data have been smoothed with a 12 point running average method. The large change in the $\delta^{13}C$ composition occurs coincident with the railway construction. Between 1910 and 1948 (Trend *A*) the $\delta^{13}C$ composition showed a long term increase. This we suggest is related to the large number of hurricanes in this interval which caused the isolation of Florida Bay to break down. From 1948 to 1986 (trends *B* and *D*) the $\delta^{13}C$ composition became more depleted coincident with a reduction in the number of hurricanes. The only exception to the decreasing isotopic trend occurred between 1959 and 1966 (trend *C*) which coincided with three hurricanes.

is already near the maximum attainable under evaporative conditions (Swart et al., 1989) and therefore further evaporation would not appreciably increase the $\delta^{18}O$. Second, changes in the carbon balance may be more susceptible to variations in hurricanes and storms while oxygen may be more function of rainfall amounts, a parameter which is unrelated to hurricane intensity.

Changes in the oxygen isotopic composition related to railway construction

Although there appears to be an increase in $\delta^{18}O$, similar to $\delta^{13}C$, coincident with railway construction, on closer inspection it is evident that the lower $\delta^{18}O$ values actually occurs several years before the change in $\delta^{13}C$. We can only speculate that the low $\delta^{18}O$ values between 1895 and 1905 are related to a substantial lowering of the salinity at this time. Although no salinity measurements exist from this period, support for this hypothesis is provided by reports from sponge fishermen who noted a severe decline in the sponge populations at this time, a phenomenon they attribute to an influx of freshwater. In addition there are reports at this time of freshwater off Key West (Zieman, pers. comm.). In addition to the large changes in $\delta^{18}O$ which are not associated with railway construction, there is a small, but nevertheless statistically significant increase in the mean $\delta^{18}O$ of the coral skeleton coincident with this event. The mean $\delta^{18}O$ of the skeleton increases from -2.75‰ in pre-railway skeleton to -2.44‰ for the period between 1905 and 1986. Using the relationship shown in Fig. 14, this increase is equivalent to an average increase in salinity of approximately 0.8 g/kg.

A further influence that the construction of the railway may have had on the salinity of Lignumvitae Basin is the reduction in the range of the inter and intra-annual salinity values. This is evident in the standard deviation of the annual average $\delta^{18}O$ values. Prior to 1905 the standard deviation is 0.46‰ compared to 0.27‰ for the years between 1905 and 1986. This suggests a larger inter-annual variation in $\delta^{18}O$ and hence salinity prior to the construction of the railway.

Relationship of isotopic data to growth rate

The growth rate of the FB-6 coral averages 5.07 mm a year, but is punctuated by two abrupt changes, one at 1883 and one at 1928. We believe that these changes in growth rates were probably caused by large storms which altered the growth orientation of the colony. Although the coral colony is large, it is at the present day not cemented to the bottom and could be easily moved by currents and wave action.

It has been previously suggested that the $\delta^{13}C$ and $\delta^{18}O$ of the coral skeleton is related to growth rate, with slower growth rates corresponding to more ^{18}O-enriched skeletal carbonate (McConnaughey, 1989a,b). If this were in fact instrumental in causing isotopic variation, then there should be pronounced changes in both the $\delta^{13}C$ and $\delta^{18}O$ associated with the large decrease in growth from 1927 to 1928 and from 1883 to 1884. No such relationships were observed suggesting that growth rate is not important in controlling either $\delta^{13}C$ or $\delta^{18}O$ in this coral.

5. Conclusions

(1) The $\delta^{13}C$ and $\delta^{18}O$ of the coral skeleton of this specimen of *Solenastrea bournoni* records the long term environmental conditions within Florida Bay, in particular changes in the salinity and the amount of oxidized organic carbon being released from the sediments.

(2) The $\delta^{18}O$ of the coral skeleton can be correlated with the salinity in the basin from which it was collected between the period 1956 and 1986. For the 197 months for which salinity data were available an r value of 0.41 has been determined, statistically significant at greater than 99.99% confidence limits. The carbon isotopic composition showed no statistically significant relationship with either temperature or salinity over this period.

(3) Based on the correlation between skeletal $\delta^{18}O$ and salinity between 1956 and 1986, our data suggests that there is no evidence of a long term increase in the salinity of the Bay from where this coral was collected related to either climatic or anthropogenic influences. Such anthropogenic influences include the alteration of water flow

which occurred as a result of various engineering projects which were carried out during 1950s and 1960s designed to control water levels in the Everglades and adjacent agricultural areas. A small increase in $\delta^{18}O$ was noticed coincident with the construction of the Florida East Coast Railway between 1907 and 1910. Based on the coral isotopic record, the salinity of the basin in which this coral grew has varied only between 34 and 42 g/kg throughout the lifespan of this coral. Employing transfer functions calculated using the instrumental data available for this period, we have estimated salinities in other portions of Florida Bay.

(4) The $\delta^{13}C$ records of the coral skeleton shows two major changes. The first occurred between 1907 and 1910 and is coincident with the construction of the railway between Miami and Key West. We suggest that this process restricted access between the Bay and the reef tract allowing a build up of the products of the oxidation of organic carbon within the Bay. The second change occurred between 1948 and 1986 and is manifested as a continual decrease in the carbon isotopic ratio of the coral. Between 1910 and 1948, the large number of hurricanes promoted the continual flushing of the system and export of organic rich sediments out of the Bay. After 1948, the number of hurricanes decreased, allowing the organic material to be retained in the Bay. Throughout the period between 1910 and 1948 the isotopic records of both carbon and oxygen exhibit rapid changes. The $\delta^{13}C$ changes form low to high values while the $\delta^{18}O$ varies from high to low values. These changes are approximately coincident with major hurricanes.

Acknowledgments

The authors would like to thank Amel Saied, Jim Leder, and Michelle Lopez for help with analyses. The paper benefitted from reviews by S. Savin and an anonymous reviewer. This work was partially supported by the South Florida Water Management District. Dr. D. Rudnick is thanked in this regard.

References

Boesch, D.F., Armstrong, N.E., DiElia, C.F., Maynard, N.G., Paerl, H.W., and Williams, S.L., 1993. Deterioration of the Florida Bay ecosystem: an evaluation of the scientific evidence. Rep. Working Group Florida Bay, Natl. Fish Wildl. Found., South Fla. Water Manage. Distr., 27 pp.

Davis, J.C., 1973. Statistics and Data Analysis in Geology. Wiley, 550 pp.

Dodge, R.E. and Thompson, J., 1974. The natural radiochemical and growth records in contemporary hermatypic corals from the Atlantic and Caribbean. Earth Planet. Sci. Lett., 23: 313–322.

Dodge, R.E., Jickells, T.D., Knap, A.H., Boyd, S. and Bak, R.P.M., 1984. Reef-building coral skeletons as chemical pollution (phosphorous) indicators. Mar. Poll. Bull., 15: 178–187.

Emiliani, C., Hudson, J.H., Shinn, E.A. and George, R.Y., 1978. Oxygen and carbon isotopic growth record in a reef coral from the Florida Keys and a deep-sea coral from Blake Plateau. Science, 202: 627–629.

Gonfiantini, R., 1986. Environmental isotopes in lake studies, In: P. Fritz and J.Ch. Fontes (Editors), Handbook of Environmental Isotope Geochemistry. Elsevier, Amsterdam, 2, pp. 113–168.

Hudson, J.H., Shinn, E.A., Halley, R.B. and Lidz, B. 1976. Sclerochronology—a tool for interpreting past environments. Geology, 4: 360–364.

Hudson, J.H., 1981a. Growth rates in *Montastraea annularis*: As record of environmental change in Key Largo corals reef marine sanctuary, Florida. Bull. Mar. Sci., 31: 444–459.

Hudson, J.H., 1981b. Response of *Montastraea annularis* to environmental change in the Florida Keys. Proc. 4th Int. Coral Reef Symp., Manila, pp. 233–240.

Hudson, J.H., Powell, J.V.D, Robblee, M.B. and Smith, T.J., 1989. A 107-year-old coral from Florida Bay: barometer of natural and man-induced catastrophes? Bull Mar. Sci., 44: 283–291.

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

Leder, J.J., Szmant, A.M. and Swart, P.K., 1991. The effect of prolonged "bleaching" on skeletal banding and stable isotopic composition in *Montastraea annularis*. Coral Reefs, 10: 19–27.

Leder, J.J., Swart, P.K., Szmant, A.M., Forrester, A. and Dodge, R.E., 1992. The control of O and C isotopes in coral skeletons: experimental studies. In: Abstr. 7th Int. Coral Reef Symp., Guam, p. 100C.

Leder, J.J., Szmant, A.M. and Swart, P.K., 1994. High-resolution ^{18}O records from the Caribbean coral *Montastraea annularis*. Field calibration study. In: ASLO Meet. Miami., Abstr., 34.

Leder, J.J., Swart, P.K., Szmant, A. and Dodge, R.E., 1996. The origin of variations in the isotopic record of scleractinian corals: I. Oxygen. Geochim. Cosmochim. Acta, in press.

Lloyd, M., 1964. Variations in the carbon and oxygen isotope

ratios of Florida Bay mollusks and their environmental significance. J. Geol., 72: 84–111.

McConnaughey, T.A., 1989a. ^{13}C and ^{18}O disequilibrium in biological carbonates: I. Patterns. Geochim. Cosmochim. Acta, 53: 151–162.

McConnaughey, T.A., 1989b. ^{13}C and ^{18}O disequilibrium in biological carbonates: II. In vitro simulation of kinetic effects. Geochim. Cosmochim. Acta, 53: 151–162.

McIvor, C.C., Levy, J.A. and Bjork, R.D., 1994. Changes in freshwater inflow from the Everglades to Florida Bay including effects on biota and biotic processes: a review. In: S.M. Davis and J.C. Ogden (Editors), Everglades. St. Lucie Press, 440 pp.

Meyers, J., Swart, P.K. and Meyers, J., 1993. Geochemical evidence for groundwater behavior in an unconfined aquifer, South Florida. J. Hydrol., 148: 249–272.

Patterson, W.P. and Walters, L.M., 1994. Depletion of ^{13}C in seawater CO_2 on modern carbonate platforms: Significance for the carbon isotopic record of carbonate. Geology, 22: 885–888.

Robblee, M.B., Tilmant, J.T. and Emerson, J., 1989. Quantitative observations of salinity. Bull. Mar. Sci. Abstr., 44: 523.

Smith, T.J., Hudson, J.H., Robblee, M.B., Powell, G.V.N. and Isdale, P.J., 1989. Freshwater flow from the Everglades to Florida Bay: A historical reconstruction based on fluorescent banding in the coral *Solenastrea bournoni*. Bull. Mar. Sci., 44: 274–282.

Swart, P.K., Sternberg, L., Steinen, R. and Harrison, S.A., 1989. Controls on the oxygen and hydrogen isotopic composition of waters from Florida Bay. Chem. Geol. (Isot. Geosci. Sect.), 79: 113–123.

Swart, P.K., Burns, S.J. and Leder, J.J., 1991. Fractionation of stable isotopes of O and C in CO_2 during the reaction of calcite with phosphoric acid as a function of temperature and technique. Chem. Geol. (Isot. Geosci. Sect.), 86: 89–96.

Weber, J.N. and Woodhead, P.M.J., 1972. Temperature dependence of oxygen-18 concentration in reef coral carbonates. J. Geophys. Res., 77: 463–473.

Wellington, G.M. and Glynn, P.W., 1983. Environmental influences on skeletal banding in eastern Pacific (Panama) corals. Coral Reefs, 1: 215–222.