Marine & Environmental Sciences Faculty Articles   Department of Marine and Environmental Sciences

1-1-1983

Environmental Correlates of Hermatypic Coral (Montastrea annularis) Growth on the East Flower Gardens Bank, Northwest Gulf of Mexico

Richard E. Dodge
Nova Southeastern University, dodge@nova.edu

Judith C. Lang
University of Texas - Austin

Find out more information about Nova Southeastern University and the Halmos College of Natural Sciences and Oceanography.

Recommended Citation

Environmental correlates of hermatypic coral (*Montastrea annularis*) growth on the East Flower Gardens Bank, northwest Gulf of Mexico[1]

Richard E. Dodge
Nova University Oceanographic Center, 8000 N. Ocean Drive, Dania, Florida 33004

Judith C. Lang
Department of Zoology, University of Texas at Austin 78712

Abstract

Time series of annual linear growth increments from 12 *Montastrea annularis* (E. and S.) collected at the East Flower Gardens Bank reef in the northwestern Gulf of Mexico have a common pattern. This is best expressed in an index master chronology (average by year of the annual percentage deviations from the mean of each coral).

Comparisons with time series of environmental data indicate that coral extension rates vary positively with seasonal (February through May—4 months) surface water temperature and negatively with annual discharge of the Atchafalaya River. We propose that secular variations of water temperature and other parameters are the major long term controls of coral growth in the area. Our data do not support the view that sinking of the Flower Gardens reef, caused by catastrophic collapse of the underlying substrate, has been a prime influence on the corals.

Near the continental shelf break of the northwestern Gulf of Mexico a series of prominent, relatively shallow, submarine banks rises abruptly above the smooth, gently sloping bottom (Gallaway 1981). Although a few species of fire and reef corals grow on many of the bank crests, the East and West Flower Gardens Banks are exceptional. They are near the continental shelf margin (Fig. 1) about 200 km SSW of Galveston, Texas, and are usually bathed by surface waters of the open gulf, which are less variable in temperature and salinity than waters closer to shore. The upper portions of the Flower Gardens Banks are elevated above the surrounding turbid bottom water (nepheloid layer). Their crests (at depths <20 m) are capped by the only true coral reef communities in the northwestern Gulf of Mexico, which are also among the most northerly coral reefs in the western Atlantic biogeographic province. Zonation patterns on the reefs resemble those in parts of the Florida reef tract (Gulf of Mexico: Fish. Manage. Counc. unpubl.), the Caribbean, and the southern Gulf of Mexico (Bright 1977); however, the diversity of hermatypic (zooxanthellae-containing) corals is relatively reduced (Tresslar 1974) in comparison to Jamaica (Wells and Lang 1973).

The inner Texas-Louisiana continental shelf is one of the most extensively developed areas in the world for oil and natural gas resources. Many of the shelf-edge banks, including the Flower Gardens, are formed by deep evaporite deposits extruding upward through a thick sediment overburden. Beds flanking these salt domes or diapirs have often formed traps for hydrocarbon accumulation. Exploration and production drilling operations are now taking place on or near at least seven of the features (Gettleson and Putt unpubl.), but there have been few definitive studies of long term controlling environmental factors in the area and of the effects of human activities over long periods (Gallaway 1981).

To evaluate the long term effect, if any, of drilling-fluid pollution from exploratory well-drilling activity within several kilometers of the Flower Gardens from 1974

---

to 1978, Hudson and Robbin (1981) in 1979 cored skeletons of 12 specimens of *Montastrea annularis* growing at 20-m depth on the south-central part of the East Flower Gardens Bank (27°53'N, 93°38'W). Skeletal cores were slabbed and X-radiographed to reveal annual density bands (e.g. Knutson et al. 1972; Macintyre and Smith 1974; Dodge et al. 1974; Hudson et al. 1976). Linear growth per year was next measured on each coral. Because the cores were of different length, the measurements spanned intervals from as long as 93 years (1887–1979) to as short as 34 (1946–1979). Hudson and Robbin (1981) found that annual growth, which had averaged 8.9 mm between 1907 and 1956, declined abruptly during 1957 and remained low for the following 22 years (avg 7.2 mm). This decrease in linear growth clearly predated the initiation of active drilling in the vicinity of the Flower Gardens. Long term environmental data, however, were unavailable to critically assess other potential controlling factors.

Hudson and Robbin's growth information for *M. annularis* has been used in support of an intriguing hypothesis (Rezak and Bright 1981). Evaporite deposits in the diapir underlying the East Flower Gardens are dissolving (Bright 1977; Brooks et al. 1979), so that cavities from which salt has been removed are probably forming below the reef on the East Flower Gardens Bank. Rezak and Bright (1981) have suggested that "catastrophic collapse" (of the order of 6 m or more) of the reef above such a cavern occurred in 1957. As is well known (e.g. Goreau and Goreau 1959; Vandermeulen et al. 1972), the skeletal calcification of reef corals such as *M. annularis* is correlated with the photosynthetic activity of their zooxanthellae (dinoflagellate algal endosymbionts). The decrease in ambient light available for photosynthesis incurred by an increase of 6 m in water depth is suggested to account for the abrupt change in rates of coral growth seen in the cored corals (Rezak and Bright 1981; Shinn 1981). In support of their hypothesis, Rezak and Bright reported that several north–south seismic profile records por-
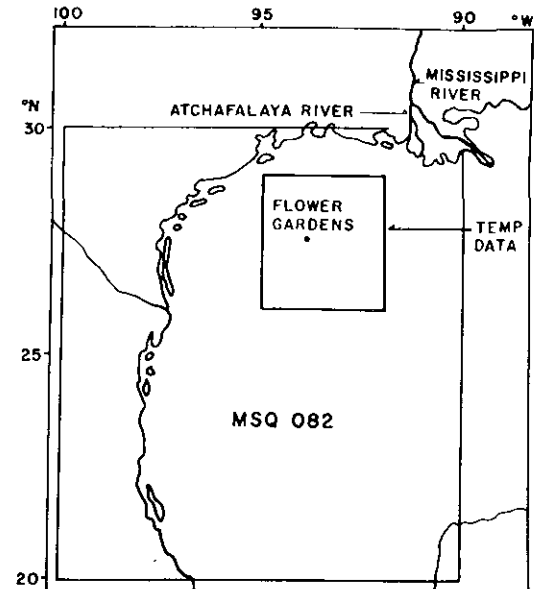

Fig. 1. Map of the Gulf of Mexico showing location of the East Flower Gardens Bank reef, Marsden Square 082, and the smaller area from which National Climatic Center surface water temperature and other climatic data were obtained (*see text*).

tray a series of shallow depressions across central portions of the bank, although there was little evidence of a crestal graben.

We present here evidence that other mechanisms can better explain the changes in growth of the 12 corals collected by Hudson and Robbin at the East Flower Gardens Bank. We first review the available data on coral growth and process the information into a convenient statistical format. We then compare coral growth with the historical record of several environmental climatic factors, compiled from various sources. The results of this analysis indicate that secular environmental change, particularly sea-surface water temperature, is probably responsible for the observed variations in growth.

Table 1. Linear growth information for the 12 *M. annularis* corals of Hudson and Robbin (1981).

Coral No.	Timespan, 1979 to	No. of years	Mean growth rate ($cm \cdot yr^{-1}$)	SD
1	1914	66	0.993	0.131
2	1892	88	0.722	0.104
3	1912	68	0.792	0.156
4	1923	57	1.058	0.168
5	1904	76	0.755	0.135
6	1918	62	0.836	0.140
7	1921	59	0.897	0.157
8	1946	34	0.966	0.201
9	1887	93	0.715	0.133
10	1903	77	0.731	0.173
11	1903	77	0.816	0.180
12	1908	72	0.874	0.109

ANOVA for 12 coral means

H_o: There are no differences between mean growth rates of the 12 corals

Source	SS	df	MS
Total	27.0814	828	—
Group	9.2927	11	0.8448
Error	17.7887	817	0.0218

$F = 38.80$ where $F_{0.05(1) \; 11, \; 500} = 1.81$
Thus, reject H_o, $P < 0.0005$

Methods

Coral data—We have used two types of data for analyzing coral growth. The base data consist of the annual extension measurements on each of the 12 corals as provided by Hudson and Robbin (1981). In addition to this information, we followed a standard procedure of tree-ring analysis or dendrochronology (Fritts 1976). The yearly growth values of each coral were divided by its particular mean growth rate (as determined over all years of measurement of that specimen). This provided a normalized or "index" series for each coral with a mean of 1.00 and annual values expressed as percentages of that mean.

Environmental data—The National Climatic Center archives by date and place of observation sea-surface temperature and other information taken by vessels of opportunity all over the world. We

obtained their records from 1949 to 1979 (max timespan) from Marsden Square 082 (20°–30°N by 90°–100°W). Because this area was very large in comparison to the Flower Gardens, we reduced data from a smaller portion (26°–29°N by 92°–95°W: Fig. 1) by averaging all observations for a particular parameter per day within the designated area. Daily means or single values (for days when there was only one measurement) were averaged for each month in each year. Monthly means were averaged into seasonal and annual values for each year to construct historical time series. Numbers of observations per year ranged from 200 to 1,000. Environmental parameters of surface water temperature, wave height, and wind speed (squared) were extracted and reduced in this way.

We also obtained annual data on discharge of the Mississippi and Atchafalaya Rivers at their mouths covering the period 1928–1979 (Cunningham pers. comm.), annual suspended total solids over 1952–1979, and average sediment concentrations over 1952–1979 (Tuttle and Combe 1981). We chose these data because of possible salinity or other effects from river discharge.

Results

Coral growth—To evaluate coral growth over time, Hudson and Robbin (1981) calculated averages by year of the linear growth measurements in all available corals. In older portions of their chronology the number of measurements per year decreases because the core lengths, and hence the number of years measured on each coral, are not the same. All portions of the chronology are therefore not equally weighted, which can introduce a bias unless all corals have the same average growth rate. For testing differences between the average growth rate of individual corals (Table 1), we used a one-way ANOVA (Zar 1974). Results showed a significant difference between individual coral means ($F = 38.80$, $P < 0.0005$) which indicates that average growth rate by year is only representative of all the corals when sample size per year remains constant.
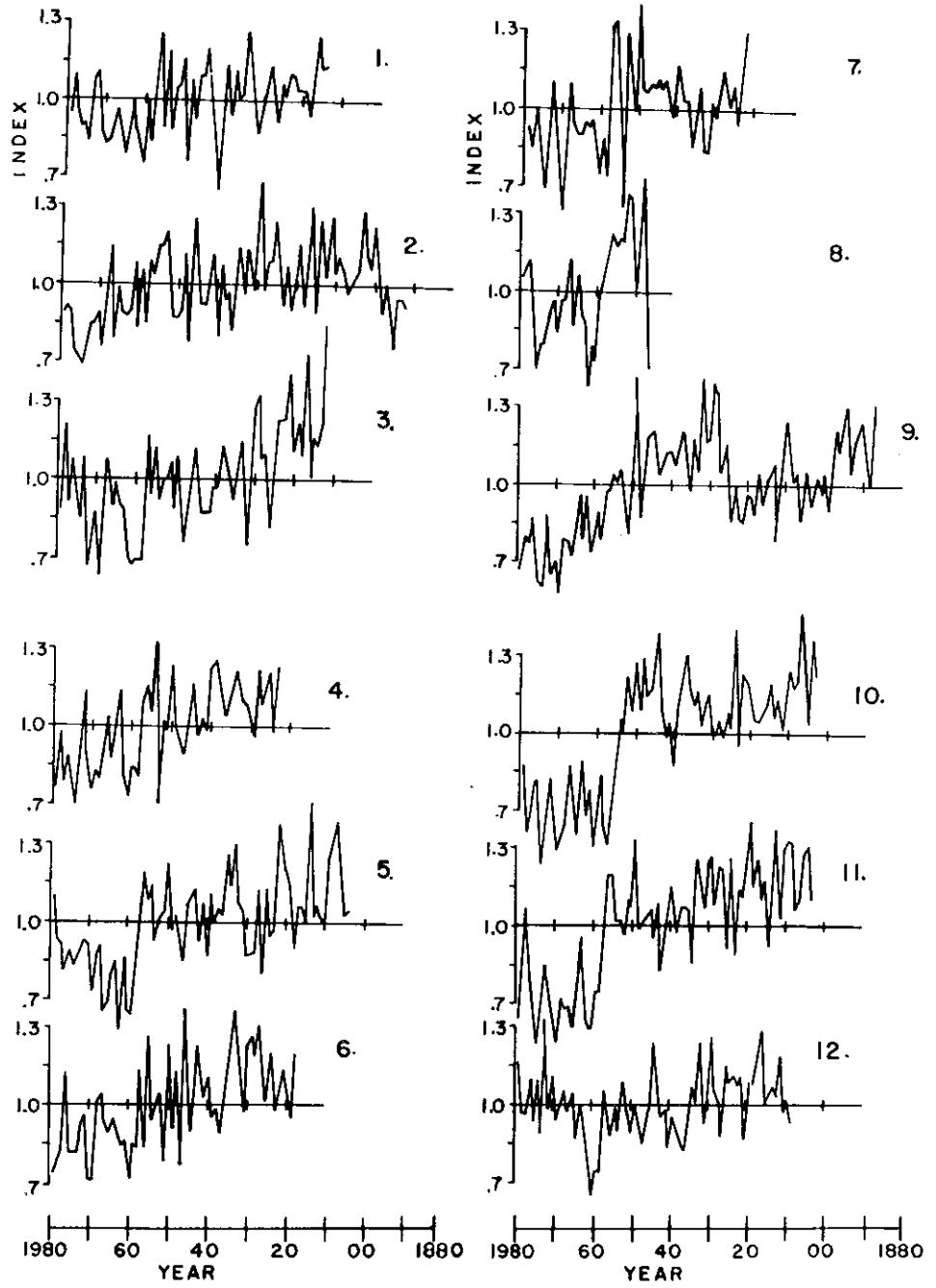
Fig. 2.   Index chronologies (annual linear growth values of each year divided by the mean for all years in a given coral) for each of the 12 corals comprising Fig. 3.
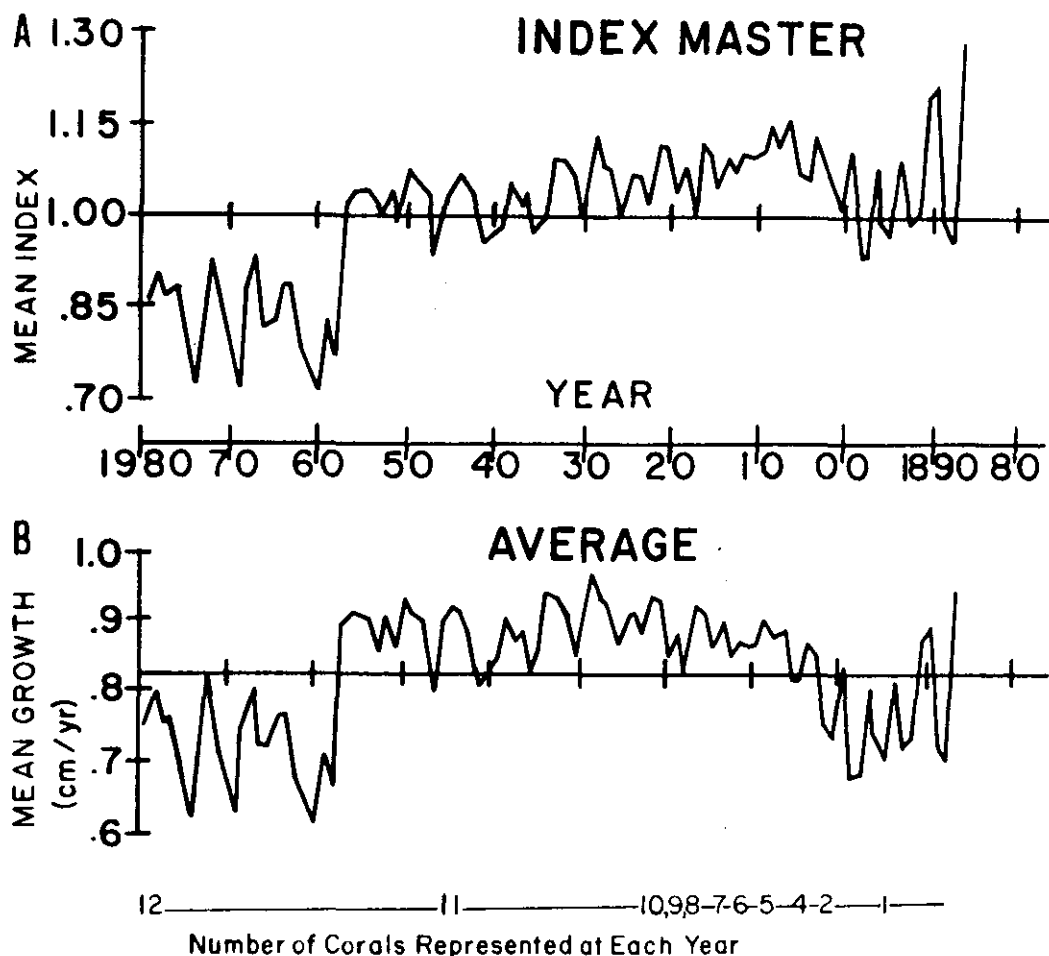
Fig. 3. A. Index master chronology of 12 *M. annularis* corals from the East Flower Gardens Bank. Calculation procedure described in text. B. Average linear growth ($cm \cdot yr^{-1}$) of above corals calculated in the manner of Hudson and Robbin (1981). Notation at the bottom indicates number of growth increments present in each year.

To best expose the common trend of all corals, we averaged the index values of all 12 corals (Fig. 2) by year to form an "index master chronology." Figure 3A presents the index master derived by our method and Fig. 3B presents the chronology derived by Hudson and Robbin (1981). Both express similar features in the 1946–1979 portion because all corals are equally represented. In older regions the chronologies are considerably different. For example, Fig. 3B shows an apparent increase in growth from the 1890s to 1920 while the index master in Fig. 3A shows a gradual decline over the same period. The index master more accurately reflects long term trends because it is relatively independent of the effect of individual differences in those years when measurements from all corals are not equally represented.

We next assessed the relationship between the growth records of the 12 corals (Fig. 2). Over the period 1946–1979 (34 years) which was common to all corals, correlation coefficients were calculated between the annual growth data for each nonredundant pair of the 12 corals and

Table 2. Correlation coefficients between coral time series over the period 1946–1979 (34 years). For $r > 0.33$, $P > 0.05$.

Coral No.	1	2	3	4	5	6	7	8	9	10	11	12	Index master
1	—												
2	0.32	—											
3	0.30	0.25	—										
4	0.68	0.21	0.28	—									
5	0.57	0.28	0.38	0.48	—								
6	0.33	0.58	0.35	0.41	0.28	—							
7	0.43	0.37	0.35	0.37	0.47	0.60	—						
8	0.33	0.44	0.33	0.36	0.57	0.17	0.35	—					
9	0.19	0.48	0.35	0.43	0.30	0.48	0.57	0.34	—				
10	0.38	0.33	0.17	0.39	0.50	0.48	0.43	0.45	0.62	—			
11	0.50	0.38	0.51	0.59	0.66	0.41	0.62	0.61	0.74	0.59	—		
12	0.22	−0.08	0.23	0.17	0.28	0.08	0.12	0.11	−0.12	−0.02	−0.02	—	
Index master	0.64	0.58	0.56	0.67	0.73	0.66	0.74	0.67	0.72	0.72	0.87	0.20	—

the index master. (For correlation coefficients it makes no difference whether raw or index values are used.) A fairly high degree of correlation is indicated for most pairs (Table 2). This procedure was performed over longer timespans using only those coral series available, and between-coral correlation remained high. A nested ANOVA design (Snedecor and Cochran 1975) was also used to quantify the similarity of coral growth time series within the available group. The method compared the amount of variation between yearly averaged index values to variation of the index values within each year in the master chronology. Results (presented in Table 3) indicate that the proportion of variation between years is high relative to that within years and is statistically significant ($P < 0.0005$).

Both the correlation and ANOVA analyses demonstrate that the growth rate patterns of individual corals composing the master chronology share common features. When the coral growth series are averaged into the index master chronology (Fig. 3A), individual or more random variations are suppressed and the common pattern is emphasized.

Environmental comparisons—Seasonal and annual surface water temperatures were compared with the coral index master. In general coral growth was higher in years of warmer water temperature. The highest correlation, $r = +0.53$ (statistically significant at the $P < 0.01$ level), of the coral index master with a temperature time series was that with average winter–spring surface water temperature (February–May: 4-month avg) over the period 1950–1979. Other surface water temperature chronologies encompassing this

Table 3. Nested ANOVA to examine proportion of variation between yearly index means as opposed to variation within yearly averages.

Source	SS	df	MS	Estimated MS	% Estimated MS
Between years	11.9406	92	0.1298	0.1024	38.5
Within years	14.5557	736	0.0198	0.0198	61.5
Total	26.5627	828	—	0.0322	100.0

H_o: There is no difference in variation between years as opposed to within years
$F = 6.56$, $F_{0.05(1) \, 100, \, 500} = 1.29$
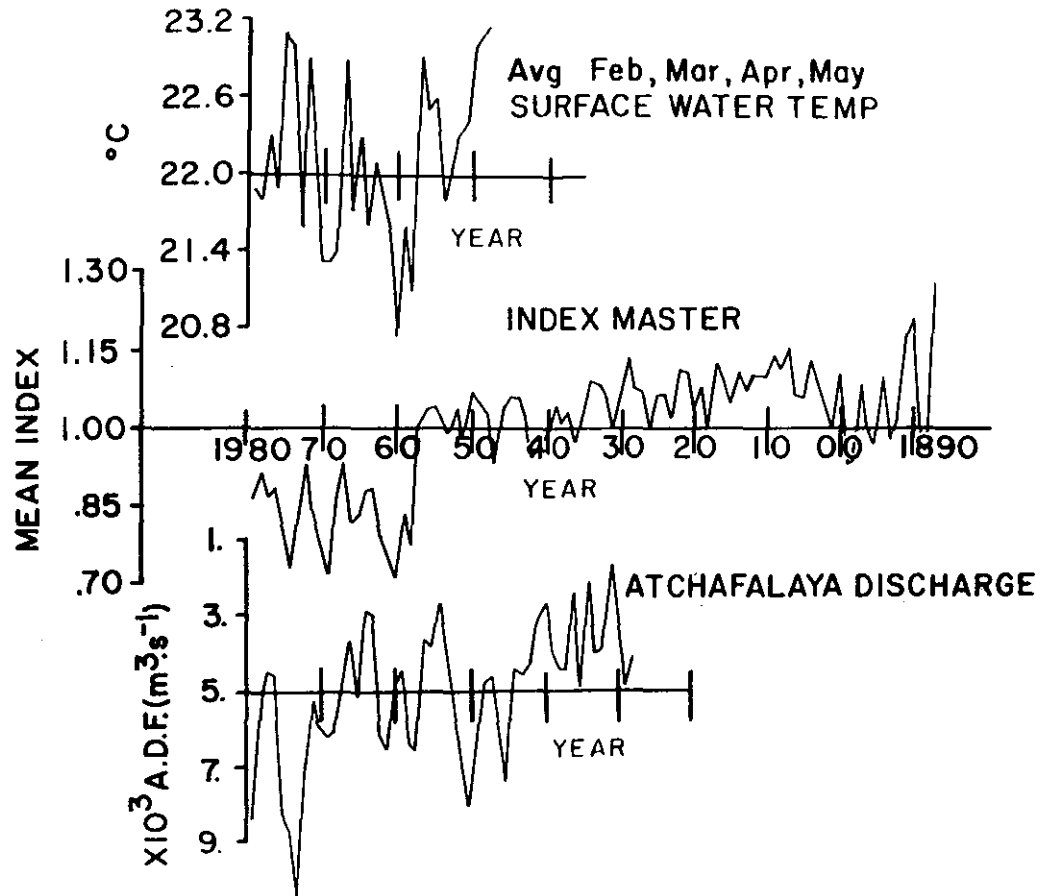Thus, reject H_0; $P < 0.0005$.

Fig. 4. Comparison of seasonal surface water temperature (February–May: 4-month avg over the period 1950–1979), coral index master chronology, and discharge of the Atchafalaya River (average daily flow, A.D.F., over the period 1928–1979). Abscissa for discharge is inverted.

season (e.g. December–May: 6-month avg) gave high correlations ($r = +0.48$) as well. Figure 4 illustrates the match of average February–May water temperature with the index master.

The general features of the growth-temperature relationship are the following. The 12 specimens of *M. annularis* and winter–spring water temperature both show an overall decline from 1950 to 1960, with a marked depression after 1957. From the early 1960s to 1979, coral growth is variable and lower than the pre-1957 values. Over the same period variations in yearly sea-surface temperature are generally in phase with those in growth but their trend gradually in-

creases to pre-1957 levels. The good correlation of winter–spring temperature with the coral growth series and the striking occurrence of lowered water temperature and coral growth in the years immediately after 1957 suggest that sea temperature exerts a major control on the growth of corals in this region. The lack of complete correspondence and the divergence of the temperature-growth trends from about 1970 indicate that other factors also influence and control coral growth.

Wave height and wind speed squared (a measure of wind stress) were used as indicators of sea state, and seasonal and monthly time series of these were, in

general, positively correlated with each other. Sea state was considered important because temperature was measured at the surface while the corals grew at 20-m depth. Thus, adequate mixing of the surface layer was necessary to justify our use of the temperature data. There were no anomalous calms over the period of record (1950–1979). The most direct index of water motion and turbulence is probably wave height, and there were no significant correlations between this variable and the coral index master.

Fluid and sediment discharge data for the Mississippi and Atchafalaya Rivers were also pertinent environmental variables to examine. At least in winter and early spring, the general flow of surface water along the Texas-Louisiana shelf is to the west via the Central Gulf Current (Gallaway 1981). Salinity off the shelf is influenced by this current and by river discharge (Smith 1980; Temple et al. 1977). After periods of high river discharge, generally between January and June (van Heerden and Roberts 1980), lower salinities occur over much of the northwestern shelf and even extend as far seaward as the Flower Gardens (McGrail and Horne 1981; Etter and Cochrane 1975). Although detailed salinity-depth studies have not been performed for the Flower Gardens area, lower salinity water from river discharge can at least occasionally reach depths of about 15–20 m (McGrail and Horne 1981; Trocine and Trefrey unpubl.).

Since the middle 1800s the Atchafalaya River has accepted increasingly greater volumes of Mississippi discharge (30–35% at present) due in part to removal of a major log jam and to other alterations by man. The combined average discharge of both rivers has remained relatively constant, but discharge of the Atchafalaya has increased significantly (Tuttle and Combe 1981). The relative proportions of Atchafalaya and Mississippi water extending into the western gulf are not known, but Atchafalaya water must be more prominent due to the western location of the river mouth (Fig. 1) which separates its discharge from the more direct influence

Table 4. Correlation coefficients calculated between the indicated time series over the period 1950–1979 (30 years). C—The coral index master; WT—surface water temperature (average monthly) for the season February–May; A—Atchafalaya annual discharge.

	C	WT	A
C	—		
WT	0.53	—	
A	−0.27	0.20	—

Multiple correlation: $r_{1.23} = 0.65$ ($P < 0.001$)
Partial correlations: $r_{12.3} = 0.62$ ($P < 0.001$)
$r_{13.2} = -0.45$ ($P < 0.01$)

If the correlation coefficient between the coral index master and Atchafalaya discharge ($r = -0.39$) over the period 1928–1979 is substituted for the 1950–1979 value ($r = -0.27$), then
Multiple correlation: $r_{1.23} = 0.73$ ($P < 0.001$)
Partial correlations: $r_{12.3} = 0.67$ ($P < 0.001$)
$r_{13.2} = -0.60$ ($P < 0.001$)

of the east-flowing loop current (Gallaway 1981). We compared the index master coral growth chronology to the annual discharge record of both rivers individually and to their combined totals over the period 1928–1979 (52 years). In general annual coral growth was negatively correlated with annual river discharge. Most significant results (Fig. 4) were found with the Atchafalaya River, for which the correlation coefficient between coral growth and discharge was $r = -0.39$, significant at the $P < 0.002$ level. Suspended sediment load and average sediment concentration of the two rivers for the period 1952–1979 were also compared against the index coral growth time series. No statistically significant correlations were found.

Table 4 summarizes correlations between temperature and discharge. Over the period 1950–1979, corals are positively correlated to temperature and negatively correlated to discharge. The multiple correlation coefficient of corals for both temperature and discharge is high ($r = +0.65$) as are the partial correlations for corals and temperature (excluding discharge) ($r_{12.3} = +0.62$) and corals and discharge (excluding temperature) ($r_{13.2} = -0.45$). If the value of $r = -0.39$ for the growth-discharge correlation (over the pe-

riod 1928–1979) is substituted for the 1950–1979 value, the multiple correlation of corals with temperature and discharge becomes $r = +0.73$ and the partial correlations are similarly increased.

Discussion

The secular hypothesis—It is our contention, which we call the secular hypothesis, that coral growth at the East Flower Gardens Bank is best explained by secular variations in environmental parameters, most particularly, sea-surface temperature. We have shown that the record of coral extension is correlated statistically significantly with natural changes of surface water temperature since 1950, including the pronounced growth depression after 1957. Changes in surface water temperature do not explain all variability in the coral growth series. Since the 1960s coral growth has remained relatively low despite slowly rising temperatures. The coral growth series, however, shows a negative relationship with the discharge of the Atchafalaya River. In general, years of higher discharge are years of lowered growth. This is evident throughout the record and possibly most important in the 1970s when Atchafalaya discharge increased dramatically.

There are valid biological reasons to consider that temperature and river discharge can control coral growth. Most reef-building corals are limited to relatively warm ($>16°C$) tropical and subtropical waters (e.g. Wells 1957; Stoddart 1969). Coral growth rates have been shown to be positively related to water temperature in laboratory experiments (e.g. Clausen 1971; Jokiel and Coles 1977), along latitudinal gradients (e.g. Rosen 1971; Stehli and Wells 1971; Weber and White 1977) and in situ (Shinn 1966; Glynn and Stewart 1973). Dodge and Vaisnys (1975), Hudson et al. (1976), and Dodge (in press) have shown that time series of coral growth bands can be correlated with the temperature chronology of the area of growth. That the upward growth of the Flower Gardens coral

should be positively correlated with the record of winter–spring water temperature is reasonable.

The negative relationship of coral growth with river discharge is more surprising; however, river discharge could influence corals in a variety of ways. One is through the direct effects of altered salinity. Although salinity-growth relationships of corals have not been formally addressed, reef corals are generally restricted to open marine waters (Wells 1957) with some exceptions (Kinsman 1964). A low tolerance to fluctuations in salinity (Vaughan 1916; Wells 1932; Jöhannes 1975) is thought to be responsible for the lack of coral reef development near the mouths of major rivers or in some coastal regions where wide fluctuations are common (e.g. Stoddart 1969). Nevertheless, the Flower Gardens area is far removed from the coast and it must be recognized that salinity fluctuations will be very small (of the order of 3.0‰).

Another way in which river discharge could influence Flower Gardens corals is through alteration of light level if sufficient quantities of suspended material are transported across the shelf. For example, Hudson and Robbin (1981) did their sampling shortly after a period of unusually high rain and noticed a distinct lens of less saline, highly turbid water extending 6–9 m below the surface; this lens accounts for the greenish coloration in the pictures of Shinn (1981) illustrating the coring operation. Because Flower Gardens corals live at 20-m depth, ambient light availability will be important to their growth. Dustan (1975) and Baker and Weber (1975) have shown that maximum calcification and linear extension of *M. annularis* occurs within about 10 m of the surface and falls rapidly with increasing depth and decreasing illumination.

A third possibility is that the discharge chronology of the Atchafalaya River may itself be correlated with other environmental variables in the vicinity of the Flower Gardens (e.g. cloudiness, rainfall, etc.) which influence coral growth. The most likely candidate is some function of

ambient light availability, which varies inversely with river discharge and is the ultimate cause of the negative correlation between coral and discharge.

Finally, it is reasonable to suspect that there will be synergistic effects from temperature, salinity, and light extremes. Working with a species of Hawaiian reef coral under carefully controlled laboratory conditions, Coles and Jokiel (1978) found that deviation of salinity, or light, or both from optimal values may narrow the range of tolerable temperatures and interfere with various physiological functions (one of which is skeletal growth). Such synergistic effects might occur on the Flower Gardens reefs in spring, when water temperatures are still cool, and plumes of Mississippi area water have spread over the shelf.

It may be that while coral growth has been negatively correlated to Atchafalaya discharge over a long period, major effects have only recently become apparent. The pronounced drop in temperature beginning in 1957 substantially depressed growth. Subsequent discharge effects (or climatic variables related to discharge) have maintained the depression, even in the face of gradually rising temperatures. In other words, the corals may have experienced a change in state.

To confirm the secular hypothesis, longer and more complete records of environmental factors such as sea-surface temperatures, light levels, and nutrient supply would be helpful. Chronological analysis of coral growth from other locations on the reefs would bolster confidence in the generality of the relationships presented here. It should be noted that processing of coral X-radiographs by scanning densitometer techniques (Dodge and Thomson 1974; Buddemeier 1974; Buddemeier et al. 1974; Graus and Daniels 1981; Baker and Weber 1975) can provide information not only on skeletal extension, but also on density and calcification on annual and subannual time scales. These additional parameters, while related, each contain independent growth information (Dodge and Brass in

press) and could be valuable for environmental comparisons. Finally, chemical analyses of coral skeletons can provide information. For example, the water temperature at the time of formation may be approximated by $^{18}O:^{16}O$ (Weber and Woodhead 1972; Fairbanks and Dodge 1979) and Sr:Ca (Schneider and Smith 1982) ratios.

Catastrophic collapse—The reduced extension rate after 1957 of corals on the East Flower Gardens has been attributed to reduced light availability arising from deepening of the reef due to salt dome collapse (Rezak and Bright 1981; Shinn 1981). The collapse may have been catastrophic in a geologic sense; however, it seems unlikely to have occurred within a few minutes or hours. None of the *M. annularis* examined showed a change in direction of corallite growth which would indicate overturning or tipping of colonies in 1957 or in any other year covered by the cores (Hudson pers. comm.). Bright (pers. comm.) has suggested that subsidence might have taken place slowly over several months or more. Although there is geologic evidence to suggest that salt dissolution and subsequent substrate collapse may have occurred, there is little evidence (aside from that invoked from the corals) to indicate when it may have happened. The possible time frame is enormous, extending at least into the last glacial period when lowered sea level exposed the bank. Our results linking lowered water temperatures with coral growth (particularly in 1957) do not support a recent date for sinking.

The collapse hypothesis, however, remains testable by using coral growth data. For example, had sinking occurred in 1957 on the south-central part of the East Flower Gardens (vicinity of Hudson and Robbin's cores), there is no reason to suspect that it also took place on the West Flower Gardens or even over the whole extent of the East Flower Gardens Bank. As Rezak and Bright (1981) have noted, systematic coral growth rate measurements at various positions on the two reefs would represent areas which have pre-

sumably differed in recent short term tectonic activity. We add that if the annual growth patterns of corals from several locations on *both* Flower Gardens Banks are measured and show a *similar* chronology, the sinking hypothesis becomes even less likely.

Alternate hypotheses—Atmospheric and ocean dumping pollution have also been suggested as possible causes for the observed variations in coral growth over time (Hudson and Robbin 1981). Such an interpretation would require a "spike" around 1957 which caused depressed growth then and in subsequent years. Such an event, to have influenced corals well offshore, should have been relatively abrupt, widespread, and continuing. There are no historical reports, of which we are aware, of such a major pollution event in the atmosphere. The coral growth records from Puerto Rico (Dodge in press), Florida (Hudson 1981), and Bermuda (Dodge and Vaisnys 1975) do not show any indication of this feature.

Pollution from ocean dumping may be more likely. An ocean dump site about 60 km seaward of the Flower Gardens received papermill waste, chlorinated hydrocarbons, and by-products of tetraethyl lead production between about 1955 and 1973. Because ship operators may not always have been able to navigate within the designated dump sites and the actual total tonnage and composition of material dumped within the specified area is not known (Hann et al. unpubl.), it is remotely possible that a load of wastes was dropped near the Flower Gardens in 1957 and has inhibited growth ever since. Clearly it would be helpful if one could locate all dump sites, assess waste material for toxicity, and evaluate dumping frequencies. Short of this somewhat unrealistic expectation, it might be possible to use the coral skeletons themselves as pollution indicators. The $CaCO_3$ skeletons of corals are known to take up certain trace elements (e.g. Flor and Moore 1977; Thompson and Livingston 1970; Buddemeier et al. in press) and detritus (Barnard et al. 1974). Analysis might pro-

vide a pollution chronology which could be linked to the historical record.

References

BAKER, P. A. AND J. N. WEBER. 1975. Coral growth rate: Variation with depth. Earth Planet. Sci. Lett. **27**: 57–61.

BARNARD, L. A., I. G. MACINTYRE, AND J. W. PIERCE. 1974. Possible environmental index in tropical reef corals. Nature **252**: 219–220.

BRIGHT, T. J. 1977. Coral reefs, nepheloid layers, gas seeps and brine flows on hard banks in the northwestern Gulf of Mexico, p. 39–46. Proc. (3rd) Int. Coral Reef Symp., v. 1. Univ. Miami.

BROOKS, J. M., T. J. BRIGHT, B. B. BERNARD, AND C. R. SCHWAB. 1979. Chemical aspects of a brine pool at the East Flower Garden bank, northwestern Gulf of Mexico. Limnol. Oceanogr. **24**: 735–745.

BUDDEMEIER, R. W. 1974. Environmental controls over annual and lunar monthly cycles in hermatypic coral calcification, p. 259–267. Proc. (2nd) Int. Coral Reef Symp., v. 2. Brisbane.

————, J. E. MARAGOS, AND D. W. KNUTSON. 1974. Radiographic studies of reef coral exoskeletons: Rates and patterns of coral growth. J. Exp. Mar. Biol. Ecol. **14**: 179–200.

————, R. C. SCHNEIDER, AND S. V. SMITH. In press. The alkaline earth chemistry of corals. Proc. (4th) Int. Coral Reef Symp. Manila.

CLAUSEN, C. 1971. Effects of temperature on the rate of calcium-45 uptake by *Pocillopora damicornis*, p. 246–259. *In* H. M. Lenhoff, et al. [eds.], Experiments in coelenterate biology. Univ. Hawaii.

COLES, S. L., AND P. L. JOKIEL. 1978. Synergistic effects of temperature, salinity, and light on the hermatypic coral *Montipora verrucosa*. Mar. Biol. **49**: 188–195.

DODGE, R. E. In press. Growth characteristics of reef-building corals within and external to a naval ordnance range: Vieques, Puerto Rico. Proc. (4th) Int. Coral Reef Symp. Manila.

————, R. C. ALLER, AND J. THOMSON. 1974. Coral growth related to resuspension of bottom sediments. Nature **247**: 574–577.

————, AND G. W. BRASS. In press. Skeletal extension, density, and calcification of a reef coral (*Montastrea annularis*): St. Croix, U.S. Virgin Islands. Bull. Mar. Sci.

————, AND J. THOMSON. 1974. The natural radiochemical and growth records in contemporary hermatypic corals from the Atlantic and Caribbean. Earth Planet. Sci. Lett. **23**: 313–322.

————, AND J. R. VAISNYS. 1975. Hermatypic coral growth banding, an environmental recorder. Nature **258**: 706–708.

DUSTAN, P. 1975. Growth and form in the reef-building coral *Montastrea annularis*. Mar. Biol. **33**: 101–107.

ETTER, P. C., AND J. D. COCHRANE. 1975. Water temperature on the Texas-Louisiana shelf, p. 1–

24. Texas A&M Univ. Sea Grant Program. Mar. Advis. Bull.

FAIRBANKS, R. G., AND R. E. DODGE. 1979. Annual periodicity of the $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios in the coral *Montastrea annularis*. Geochim. Cosmochim. Acta **43**: 1009–1020.

FLOR, T. H., AND W. S. MOORE. 1977. Radium/ calcium and uranium/calcium determinations for western Atlantic reef corals, p. 555–561. Proc. (3rd) Int. Coral Reef Symp., v. 2. Univ. Miami.

FRITTS, H. C. 1976. Tree rings and climate. Academic.

GALLAWAY, B. J. 1981. An ecosystem analysis of oil and gas development of the Texas-Louisiana continental shelf. U.S. Fish Wildlife Serv. Office Biol. Serv. FWS/OBS-81/27.

GLYNN, P. W., AND R. H. STEWART. 1973. Distribution of coral reefs in the Pearl Islands (Gulf of Panamá) in relation to thermal conditions. Limnol. Oceanogr. **18**: 367–379.

GOREAU, T. F., AND N. I. GOREAU. 1959. The physiology of skeleton formation in corals. 2. Calcium deposition by hermatypic corals under various conditions in the reef. Biol. Bull. **177**: 239–247.

GRAUS, R. R., AND W. W. DANIELS. 1981. Optical scanning and digital analysis of coral growth bands. Geol. Soc. Am. Abstr. **13**: 463.

HUDSON, J. H. 1981. Growth rates in *Montastrea annularis*, a record of environmental change in Key Largo coral reef marine sanctuary. Fla. Bull. Mar. Sci. **31**: 444–459.

——, AND D. M. ROBBIN. 1981. Effects of drilling mud on the growth rate of the reef-building coral *Montastrea annularis*, p. 455–470. *In* Marine environmental pollution. Elsevier Oceanogr. Ser. **27A**.

——, E. A. SHINN, R. B. HALLEY, AND B. LIDZ. 1976. Sclerochronology: A tool for interpreting past environments. Geology **4**: 361–364.

JOHANNES, R. E. 1975. Pollution and degradation of coral reef communities, p. 13–51. *In* E. J. Wood and R. E. Johannes [eds.], Tropical marine pollution. Elsevier.

JOKIEL, P. L., AND S. L. COLES. 1977. Effects of temperature on the mortality and growth of Hawaiian reef corals. Mar. Biol. **43**: 201–208.

KINSMAN, D. J. 1964. Reef coral tolerance of high temperature and salinities. Nature **202**: 1280–1282.

KNUTSON, D. W., R. W. BUDDEMEIER, AND S. V. SMITH. 1972. Coral chronometers: Seasonal growth bands in reef corals. Science **177**: 270–272.

MCGRAIL, D., AND D. HORNE. 1981. Water and sediment dynamics, p. 9–45. *In* Northern Gulf of Mexico topographic feature study. Final Rep. v. 3. Dep. Oceanogr. Texas A&M Univ. Tech. Rep. 81-2-T.

MACINTYRE, I. G., AND S. V. SMITH. 1974. X-radiography studies of skeletal development in coral colonies, p. 277–287. Proc. (2nd) Int. Coral Reef Symp., v. 2. Brisbane.

REZAK, R., AND T. J. BRIGHT. 1981. Seafloor instability at East Flower Garden Bank, northwest Gulf of Mexico. Geo-Mar. Lett. **1**: 97–103.

ROSEN, B. R. 1971. The distribution of reef coral genera in the Indian Ocean, p. 263–299. *In* Regional variation in Indian Ocean coral reefs. Symp. Zool. Soc. Lond. 28.

SCHNEIDER, R. C., AND S. V. SMITH. 1982. Skeletal Sr content and density in *Porites* spp. in relation to environmental variables. Mar. Biol. **66**: 121–131.

SHINN, E. A. 1966. Coral growth rate, an environmental indicator. J. Paleontol. **40**: 233–241.

——. 1981. Time capsules in the sea. Sea Frontiers **27**: 364–374.

SMITH, N. P. 1980. Hydrographic project. *In* R. W. Flint and N. N. Reblais [eds.], Environmental studies, South Texas Outer Continental Shelf, 1975–1977, v. 3. Univ. Texas Mar. Sci. Inst.

SNEDECOR, G. W., AND W. G. COCHRAN. 1975. Statistical methods. Iowa State.

STEHLI, F. G., AND J. W. WELLS. 1971. Diversity and age patterns in hermatypic corals. Syst. Zool. **20**: 115–126.

STODDART, D. R. 1969. Ecology and morphology of recent coral reefs. Biol. Rev. **44**: 433–498.

TEMPLE, R. F., D. L. HARRINGTON, AND J. A. MARTIN. 1977. Monthly temperatures and salinity measurements of continental shelf waters of the northwestern Gulf of Mexico, 1963–1965. NOAA Tech. Rep. NMFS SSRF-707.

THOMPSON, G., AND H. D. LIVINGSTON. 1970. Strontium and uranium concentrations in aragonite precipitated by some modern corals. Earth Planet. Sci. Lett. **8**: 439–442.

TRESSLAR, R. C. 1974. Corals, p. 115–139. *In* T. J. Bright and L. H. Paquegnat [eds.], Biota of the West Flower Gardens Bank. Gulf.

TUTTLE, J. R., AND A. J. COMBE. 1981. Flow regime and sediment load entering estuaries as effected by alterations of the Mississippi River, p. 334–348. *In* Fresh water inflow to estuaries. Proc. Natl. Symp. U.S. Dep. Int. Fish Wildlife Serv. FWS/OBS.

VANDERMEULEN, J. H., N. D. DAVIS, AND L. MUSCATINE. 1972. The effects of inhibitors of photosynthesis on zooxanthellae in corals and other marine invertebrates. Mar. Biol. **16**: 185–191.

VAN HEERDEN, I. L., AND H. H. ROBERTS. 1980. The Atchafalaya delta—Louisiana's new prograding coast. Gulf Coast Assoc. Geol. Soc. **30**: 497–506.

VAUGHAN, T. W. 1916. The results of investigation of the ecology of the Floridian and Bahamian shoal-water corals. Proc. Natl. Acad. Sci. **2**: 95–100.

WEBER, J. N., AND E. W. WHITE. 1977. Caribbean reef corals *Montastrea annularis* and *Montastrea cavernosa*—long term growth data as determined by skeletal X-radiography, p. 171–179. *In* S. H. Frost et al. [eds.], Reefs and related

carbonates—Ecology and sedimentation. Am. Assoc. Pet. Geol. Stud. Geol. 4.

——, AND P. M. WOODHEAD. 1972. Temperature dependence of oxygen-18 concentration in reef coral carbonates, J. Geophys. Res. **77:** 463–473.

WELLS, J. W. 1932. Study of the reef corals of the Tortugas. Carnegie Inst. Wash. Yearbook **31:** 290–291.

——. 1957. Coral reefs. Mem. Geol. Soc. Am. **67** (1): 609–631.

——. AND J. C. LANG. 1973. Appendix. Systematic list of Jamaican shallow water Scleractinia. Bull. Mar. Sci. **23:** 55–58.

ZAR, J. H. 1974. Biostatistical analysis. Prentice-Hall.