An Assessment of Global Warming Stress on Caribbean Coral Reef Ecosystems

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ABSTRACT

There is evidence that stress on coral reef ecosystems in the Caribbean region is increasing. Recently, numerous authors have stated that the major stress results from 'abnormally high' temperatures and have implicated global warming as a cause, stating that recent outbreaks of coral bleaching are a result therefrom. However, available data sets show no discernible warming trend that could cause such bleaching and there is insufficient evidence available to label temperatures observed in coincidence with recent regional bleaching events as abnormally high, given the lack of long-term records synoptic with observations of coral ecosystem health.

KEY WORDS: Coral ecosystems, stress, bleaching, temperature, global warming.

INTRODUCTION

There are both public and scientific perceptions that Caribbean area coral reef ecosystems are under increasing stress. A synopsis of observations which lead to this perception has been provided by Williams and Bunkley-Williams (1990). A current manifestation of this stress is coral bleaching. Such bleaching results when photosymbiotic microorganisms, *e.g.*, dinoflagellates called zooxanthellae (or, red and green algae, or bacteria, or pigments of these symbionts) depart from, or are expelled from host coral animals. If bleaching continues for long enough, coral mortality can occur with subsequent bioerosion and significant destruction of the reef ecosystem (Glynn, 1989). Williams and Bunkley-Williams point out that reports of coral bleaching increased dramatically in the second half of the 1980s and state that this increase in the frequency of reports is evidence of an increase in frequency and intensity of bleaching events.

It has been clearly demonstrated that high temperature is a coral ecosystem stress which can induce bleaching. A graphic description of such an occurence is Glynn's (1989) description of coral mortality and disturbances in the tropical eastern Pacific during the 1982/83 El Niño. Glynn demonstrates that during that time, positive sea surface temperature (SST) anomalies (as deduced from ship and satellite data) of several degrees centigrade (as compared to the long term climatology) existed for several months. These anomalies were particularly high (>4°C) in the Galapagos Islands. Serious, and possibly irreversible damage resulted to coral reefs in that area. As part of this same work, Glynn and D'Croz (1991) conducted experiments in which the changes in zooxanthellae densities and coral tissue protein in *Pocillopora damicornis* were monitored as a function of time, while the coral was maintained under simulated El Niño warming conditions. At 28°C, declines in tissue protein and zooxanthellae over ten weeks were about the same as occurred at mean ambient temperature, but, at 30°C the decline was significantly greater. At 32°C, drastic declines resulted within six weeks.

This work has suggested to numerous scientists that 'high' or 'abnormally high' temperatures are a primary and increasing stress on Caribbean coral ecosystems. Temperatures over 30°C, and certainly those over 31°C, being considered evidence of that stress. Based on this perception Williams and Bunkley-Williams (1990) have proposed a model of the causes of coral reef bleaching which includes as components a deterioration of coral reef resilience, and a global warming trend. The authors postulate that El Niño, and other temporary warming events superimposed on that warming trend, push temperatures in coral reef environments over maximal values for coral tolerance during annual maxima on successive years. They note that major bleaching events occur in complexes which often include preceding events, major events, and following events which they propose are caused by the superimposed El Niño forcing three successive annual high seasonal temperatures into the regime where bleaching occurs. To accept this as a model applicable to the Caribbean one must also accept (1) that a warming trend is occuring in that region (or, alternatively, that there are increases in temperature variance that causes annual high temperatures to exceed maximal values of coral tolerance more often), (2) that El Niño events extend over two to three years, and (3) that the temperature anomalies resulting from these El Niños extend into the Caribbean area. Williams and Bunkley-Williams use this model to explain Caribbean bleaching that occurred in 1982/83 and 1987 when El Niños occurred in the Pacific, and to predict a major bleaching event in 1990. Evidence is strong that the 1990 bleaching event did occur as predicted; however, there is no evidence that an El Niño event occurred. Whether or not any other temporary warming event occurred is discussed below.

CARIBBEAN AREA REGIONAL TEMPERATURE ANOMALIES

The first Caribbean area bleaching event to receive widespread scientific attention was the one occurring in 1987. Hudson (1988), Jaap (1988), Woodley (1988), Sandeman (1988) and Williams and Bunkley-Williams (1988, 1990) all describe observations of 'unusually high' temperatures, or, high temperatures attained at an earlier than usual date, and consider such as the dominant causal stress for the bleaching. However, Losada (1988) and Knowlton (1988) note that bleaching occurred along the coasts of Venezuela and Panama, respectively, with no evidence of higher than normal temperatures.

Examined here are numerous data sets which yield information on SST, and hopefully on ambient temperatures of reef ecosystem waters. These include the following for pelagic waters.

• Blended satellite and (*in situ*) data sets in which *in situ* data are used to define 'benchmark' temperature values in regions of frequent observations and satellite data are used to define the shape of the field between these points (Reynolds, 1988).

• Multichannel SST (MCSST) data sets which are derived from satellites based on a correction (bias) derived from SST's recorded by drifting buoys. These data sets are often termed "satellite only" data in contrast to the blended data.

• Pelagic *in situ* temperature data for the upper 3 meters of the water column archived at NODC for hydrographic stations, CTD's, mechanical BT's (MBT's), XBT's.

• Pelagic sea surface temperature data reported by Elms (1991) collected by ships of opportunity since 1950. Many of these data ares from engine cooling intakes and have undergone significant quality control efforts.

Recognizing that such pelagic SST data may not reflect temperatures realized in the marginal sea environment where coral ecosystems exist, nearshore temperature data sets are also examined, although long-term records of this type that were collected on or near reef systems are lacking.

As described in an abstract by Atwood *et al.* (1988), an examination of numerous temperature data sets did not show significant regional high temperature anomalies in the Caribbean/Gulf-of-Mexico region during the 1987 bleaching event. The NOAA National Climate Data Center (NCDC) provides maps of mean monthly SST and SST anomalies that are derived from blended SST data. These maps are relatively coarse scale and are presented as having a resolution of approximately 100 kms. Anomalies are determined relative to climatology as described by Reynolds and Roberts (1987). The 1987 SST's shown in these maps are all less than 30°C with the exception of the northern Gulf of Mexico in August. Both positive and negative anomalies appeared throughout 1987 with positive anomalies usually less than 0.5°C. There was only one instance of a positive anomaly >1°C and that was in the SE Caribbean in May. Atwood *et al.* (1988) also looked at *in situ* data sets for SST as derived from National Oceanographic Data Center (NODC) archives of MBT, XBT, hydrographic station, and CTD data since 1932. They examined them in terms of mean monthly SST's for 1932 to 1986 as compared to mean monthly SST's for 1987. To do this they considered an area from 12°N to 29.2°N and 60°W to 85°W dividing it into the following latitude bands.

12.0°N to 14.7°N
14.7°N to 18.2°N
18.2°N to 21.5°N
21.5°N to 25.0°N
25.0°N to 29.2°N

Figure 1 shows plots of all of these *in situ* data as monthly means since 1965 for each of the above latitude bands. In each plot 30°C is marked by a dotted line. It is interesting to note the years when highest annual means exceeded that temperature in the two northern latitude bands, *i.e.*, in 1986 and 1987 in the 21.5°N to 25.0°N band and in 1987 in the 25.0°N to 29.2°N band. However, it also exceeded 30°C in both of those bands in 1969, as well as in the 12.0°N to 14.7°N band. In none of the bands did regional mean monthly temperatures exceed 30.2°C.

Although the common consensus seems to be that maximal temperature stress to coral animals is caused by high temperatures, (*e.g.*, temperatures exceeding 30°C, maintained for extensive periods, *e.g.*, weeks) there is also concern that rapid excursions of temperature above or below the ambient temperature to which the organism has adapted could also cause excessive stress and, perhaps, a bleaching response. To examine the possibility that change in the short term variation of SST in the Caribbean had changed coincident with the reported increases in occurences of bleaching we determined the standard deviation for the monthly means portrayed in Figure 1. These are plotted in Figure 2. Only the period of 1976 to 1987 is portrayed to allow better resolution of the standard deviations which are depicted by vertical lines for each monthly mean. Data for 1964 to 1975 are essentially the same. As shown in Figure 2 the standard deviation (SD) for the monthly means declines from north to south, *i.e*, the greater the seasonal variation the greater the SD. In the north the SD's are greater in the winter months when the position of the Bermuda high allows more fronts to enter the area from the northeast introducing significantly more temperature variability. The effect of these fronts is considerably dampened in the southern latitudes. It is also clear that this variability indicates that temperatures >30°C are reached for short periods of time in some years when summer monthly means are less than 30°C. However, as there is no indication that these monthly means increased over the period depicted, neither is there an increase in the variability of these means.

Elms (1991) has analyzed quality controlled SST data from ships of opportunity in the Caribbean and Gulf of Mexico area for the period 1950 to 1989 using the Global Ocean Surface Temperature Atlas (GOSTA, Bottomley *et al.*, 1990). He divided the region between 70°W and 90°W, 10°N and 30°N into fifteen equal areas (5° squares) and considered trends in the SST anomalies. In thirteen of the fifteen areas he analyzed, a cooling trend was indicated in the

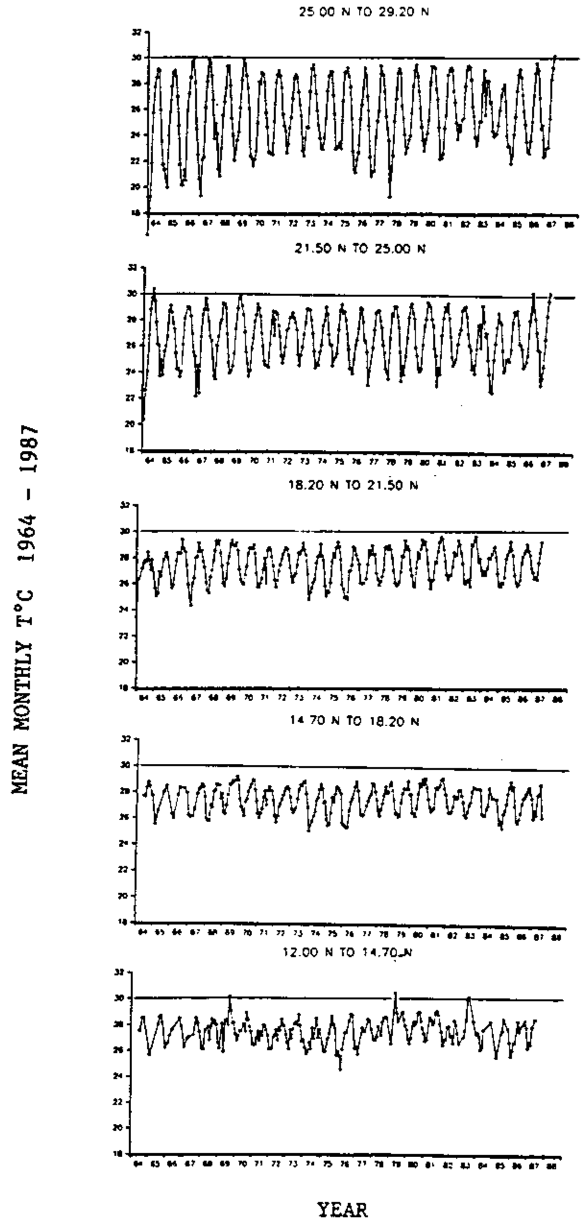

Figure 1. Plots of monthly SST means for the latitude bands indicated between 60°W and 85°W. Means are derived from *in situ* data (hydrographic stations, CTD's, XBT's and MBT's) in the NOAA/NODC archives for the period indicated. A dashed line indicates 30°C on each panel.

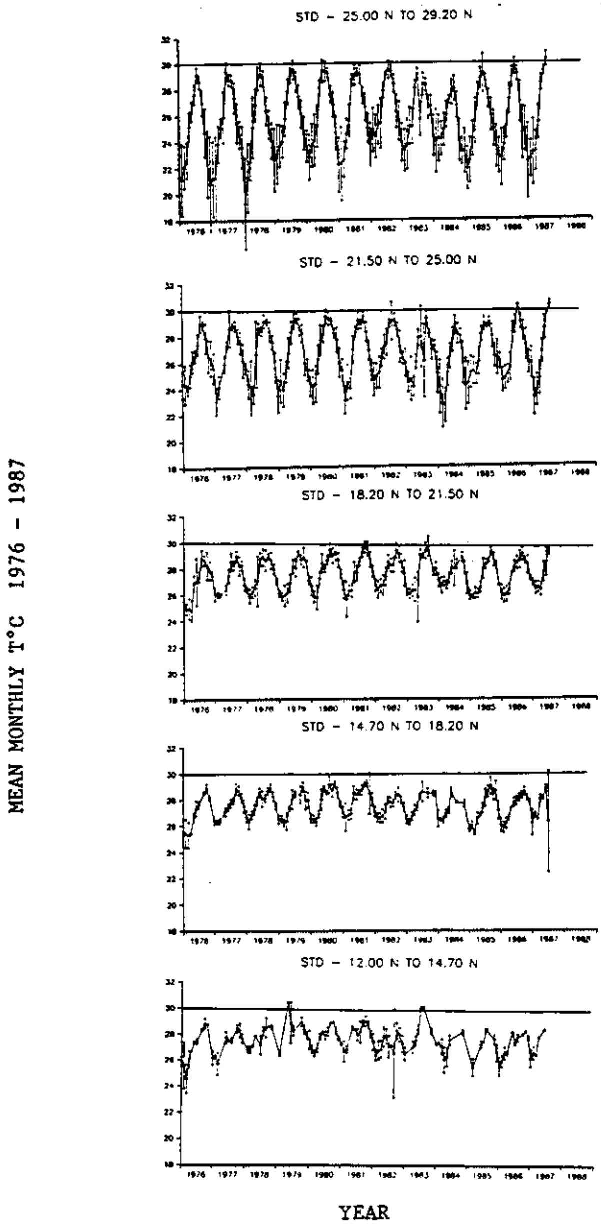

Figure 2. Plots of monthly SST means for the latitude bands indicated between 60°W and 85°W. As in Figure 1 means are derived from *in situ* data (hydrographic stations, CTD's, XBT's and MBT's) in the NOAA/NODC archives for the period indicated. A dashed line indicates 30°C on each panel.

monthly mean anomalies, varying in magnitude from -0.1°C to -0.9°C per 100 years with a regional trend of -0.5°C per 100 years. The two areas with positive trends had increases on the order of +0.2°C per century. Just as important is the fact that trend analyses of SST anomalies for those months with the highest mean monthly temperature also showed cooling trends in fourteen of the fifteen boxes with an overall regional trend of -1.0°C per 100 years. The one area with a positive trend showed an increase of +0.5°C per century. Elms notes that this regional cooling occurred in contrast to clear positive trends in the GOSTA record from 1854 to 1990 in both the northern and southern hemispheres. He concludes that there is "no link between pelagic surface water temperature trends and coral bleaching", but points out that no comparison of above normal monthly or seasonal temperatures and incidences of coral bleaching were made in his analysis. Interestingly, strong positive anomolies, similar to those noted by Atwood *et al.* (1988), are indicated for 1969 in seven of Elms' fifteen areas, as well as in the regional GOSTA means.

McCormack and Strong (1990) correlated Multichannel Sea Surface Temperature (MCSST) data with the 1987 Caribbean coral bleaching event. They state that a positive MCSST anomaly is evident for the region in 1987. However, that conclusion is based solely on a comparison of 1987 to 1986 MCSST data rather than any long term climatology, a long term MCSST climatology being unavailable due to the shortness of the MCSST record and contamination by El Chichon stratospheric aerosols early in that record (Reynolds *et al.*,1989). Strong and McCormack (1991) point out that MCSST data for the Gulf of Mexico and Caribbean show very high SST's in the Gulf of Mexico in early summer of 1990. These progress south and east to include the Straits of Florida and Florida Reef Track by mid-summer and the northern Caribbean by late summer and early fall. 1990 MCSST temperatures >30°C are common in these areas with frequent observations >31°C and some >32°C. The authors point to these high SST's as a probable causal stress for the observed 1990 coral bleaching in the region. However, no such high temperatures or positive anomalies are apparent in the blended data provided in the NOAA/NCDC 100 km resolution maps. Figure 3 shows a plot of the difference in 1990 mean monthly MCSST's and SST's derived from blended SST data products for two areas, *i.e.*, the Caribbean Sea southwest of Puerto Rico and the Straits of Florida between the middle Florida Keys and Cay Sal Bank. The MCSST data for the Caribbean was derived from a 50 km resolution map for the East Coast U.S. and that for the Straits of Florida from a 14 km resolution map for the Southeast Coast U.S. The blended data were taken from the 100 km resolution maps provided by NOAA/NCDC. Due to this difference in spatial scales, the two areas were carefully chosen so that there were minimal gradients in the data (1°C isotherms up to several hundred kilometers apart). Interpolations from the maps is considered to be better than +0.5°C. As shown

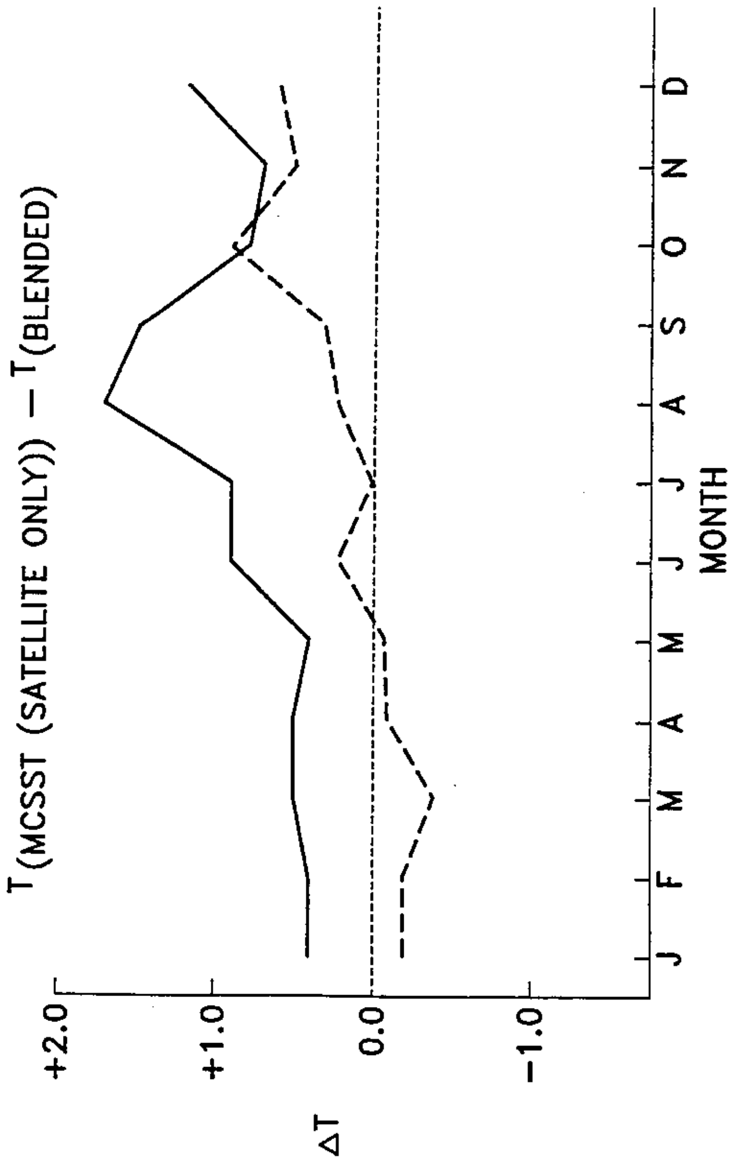

Figure 3. A plot of the difference between SST's as derived from satellite only (MCSST) product and blended *in situ* and satellite product for two areas, *i.e.*, the Straits of Florida between the middle Florida Keys and Cay Sal Bank, and the northwest Caribbean Sea just south of southwest Puerto Rico (dashed line).

in Figure 3, differences in the MCSST and blended mean monthly SST's for the Straits of Florida is within that range of interpolation through May, then it deviates significantly with the MCSST data showing temperatures 1.5°C to 1.7°C higher than the blended data in August and September. The deviations are less in Puerto Rico, but MCSST data is significantly higher in early fall. The major difference near Puerto Rico (early fall) is offset from that in the Straits of Florida (June-July-August) by about one and a half to two months, similar in timing to the progression in high MCSST temperatures from the Gulf of Mexico into the northern Caribbean noted by Strong and McCormack.

It is impossible to tell which of these two data sets, blended or MCSST, is "correct", or more correct. Clearly they are telling us different things. Given this observation, the problems in the MCSST data set described by Reynolds *et al.* (1989), and the fact that the Reynolds *et al.* paper demonstrates that *in situ* temperatures track the blended data set quite well, whereas the MCSST data do not, it seems prudent to be cautious in determining what, if anything, the MCSST data set is telling us regarding causes of coral bleaching.

NEARSHORE AND SITE SPECIFIC TEMPERATURE ANOMALIES

Scientists involved with coral reef ecosystems are correct in pointing out that pelagic SST data may not be relevant to what is happening within that marginal sea environment. The shallow waters of coastal environments will warm and cool faster than deep open ocean waters. This is evident in the MCSST data sets which show steep SST gradients across the Florida Keys, *i.e.*, between shallow Florida Bay (and Western Florida shelf) and the deeper Straits of Florida, with Florida Bay cooler in the winter and warmer in the summer. However, temperature data for such near shore systems is sadly lacking, and analysis of what data exist is difficult due to the lack of long term records which would allow a determination of whether or not any high temperatures observed are anomolous, or `unusually high'.

In an effort to establish what might be 'normal', or 'abnormal' Atwood *et al.* (1988) found two high quality data sets for nearshore temperature, one collected by Jorge Corredor and Julio Morell at the ocean edge of the southwest Puerto Rico reef system which extended from 1980 through 1988, and one of daily temperature observations made by Antonio Mendez in Bear Cut (between Virginia Key and Key Biscayne just off Miami, Florida) which extended from 1964 through 1971. The Puerto Rico data set shows no warming trend over the period of observation with the highest temperatures recorded in 1981 (29.4°C) and 1987 (29.9°C). The Bear Cut record has 2,411 observations, and for every year of record the temperature exceeded 30°C in mid- to late summer with 241 observations of >30°C and 29 observations of >31°C. The warmest years were 1964 (51 observations of >30°C), 1969 (39 such observations) and 1971 (25 observations). Atwood *et al.* used these records as evidence that high inshore temperatures in these regions seem to have been common for many years and can not be demonstrated as anomolous, or 'unusually high'.

Shinn *et al.* (1989) and Lidz and Shinn (1991) show that significant changes have occurred in coral reefs at Looe Key, a reef system south of Big Pine Key of the Lower Florida Keys (see Figure 4), during sea level changes of the past 15,000 years. As sea level rose Looe Key became submerged to a point to allow reef development close to what we now see at about 12,000 years BP. However, about 4,500 to 3,000 years BP sea level rise inundated what is now Florida Bay (Wanless and Taggett, 1989) and eventually (approximately 1,000 years BP) rose to a point that flow was possible through channels in the Lower Keys (*e.g.*, the channel at Seven Mile Bridge) establishing communication between that shallow bay and the reefs on Looe Key. Under certain conditions, *e.g.*, in times of doldrums or westerly winds) this allows water from the bay to flow out over Looe Key. Since summer bay waters are significantly warmer than those of the Straits of Florida (as evidenced by NCDC 14 km resolution maps of MCSST for the southeast U.S.) this results in a significant warming of reef waters, which could induce stress and cause coral bleaching. In fact, Looe Key Marine Sanctuary managers can predict within a week or so when such bleaching will occur once doldrum weather sets in over the Lower Keys (Billy Causey, personal communication). Thus, as in the case of Glynn's (1990) documentation of the 1982/83 El Niño high temperature caused bleaching in the tropical eastern Pacific, Looe Key seems to be a location where bleaching is caused, at least in part, by high temperatures. However, it is clear that this has and is occurring as a result of sea level changes over the past millenium. It is not a new phenomenon resulting from any recent climate warming and probably has occurred since the communication between the bay and reef was established hundreds of years ago. Accordingly it seems incorrect to term the resulting high temperatures found over Looe Key during the above described episodes as `abnormal'.

A recent effort to develop an understanding as to any relationship between temperature and coral bleaching at specific sites is described by Goreau *et al.* (1991). This group points out that the 100 km blended data set used by Atwood *et al.* (1988) is coarse, the resolution of maps published therefrom in NOAA's Oceanographic Monthly Summary being as low as 400 kms to 600 kms. Goreau *et al.* use a NOAA data product called Ocean Features Analysis (OFA) which they state has a finer resolution, and analyze trends in that data for seven sites, *i.e.*., the north coast of Puerto Rico, Jamaica, Grand Cayman Island, Florida (apparently defined as the Straits of Florida in about the same location as used above to determine differences in MCSST and blended SST data), Nassau, Bahamas and Bermuda. Data sets for the decade were developed at each of these sites by averaging the nearest values available to each site. Data used could consist of a single measurement immediately offshore, or the average of up to four measurements within several hundred kilometers of the site, weighted by

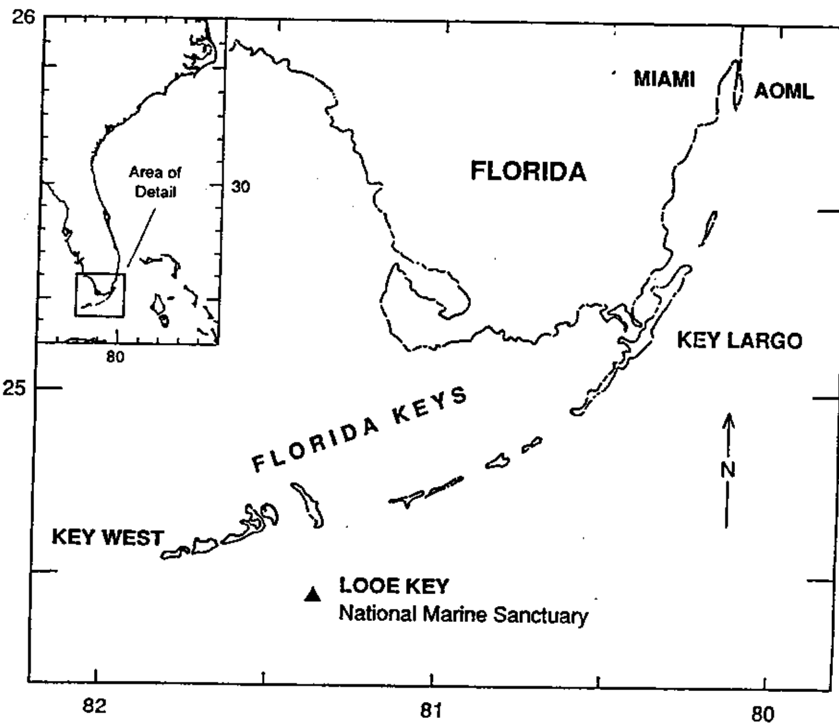

Figure 4. The location of the NOAA Looe Key Marine Sanctuary in relation to Florida and the Florida Keys.

hand according to distance. The authors state that values reported were, in effect, averaged over a spatial scale of a few hundred kilometers, and in the case of cloudy days and Puerto Rico, where data are relatively sparse, the averaging scale is larger. The authors conduct a detailed statistical analysis of the resulting data sets and conclude that at five of the sites a warming trend was observed over the decade 1981 to 1990, *i. e.*, Jamaica (0.623°C/decade), Cayman (0.492°C/decade), Florida (0.737°C/decade), Nassau (0.958°C/decade), and Bermuda (0.841°C/decade). The authors do point out that trends for one decade cannot be construed as long term. They further conclude that the spatial and temporal pattern of mass coral bleaching correlates very closely with the hottest water temperatures recorded in their data records. However, there are significant problems with this analysis which include the fact that the method for selection of temperature values for each site does not provide a resolution better than several hundreds of kilometers. Therefore the method is no more site specific than the regional analysis of Atwood *et al.* (1988) described above. Although the sites range from a latitude of 18°N to 32°N, *in situ* data are only available for the Jamaica and Cayman sites, *i.e.*, for sites between 18°N and 19.5°N. Of particular concern is the fact that the warming trends indicated by their analysis are enormous and exceed the most pessimistic predictions resulting from careful analyses of global data sets by several fold. They are in fact about equal to the increases in SST estimated by Strong (1989) for part of the same decade using MCSST data. Reynolds *et al.* (1989) show that Strong's analysis is flawed by a failure to consider the effects of the stratospheric aerosols caused by the eruption of El Chichon early in the decade under consideration. Reynolds *et al.* further demonstrate that blended and *in situ* SST data sets show no such trends.

DISCUSSION

There is ample evidence that coral ecosystems are under stress and that that stress may be increasing. Such evidences are especially apparent to observers of coral reef systems who have had consistent exposure to specific reef ecosystems for decades. Although it is not completely clear whether or not there has been an increase in the frequency and intensity of coral bleaching, or an increase in the frequency and intensity of observations, the preponderance of evidence points to an increase in occurrence. However, it is not clear what the cause of these occurrences are, or whether they occur naturally in cycles with frequencies long enough to have made detection impossible until now.

Based on the evidence discussed in this paper, it is clear that although high temperature has been demonstrated as a stress that causes coral bleaching, there is no statistically significant evidence that high temperatures are the major cause of recently documented massive coral bleaching episodes in the Caribbean region. There is even less evidence that such high temperatures have resulted from global warming. Various satellite data products have been used to indicate such warming over the past decade, but such conclusions seem to result from faulty applications of satellite information and are contradicted by *in situ* data for the same period of record. There is also minimal evidence that the Williams and Bunkley-Williams model (1990) of El Niño events superimposed on a global warming trend applies even to the extent that warm SST's associated with El Niño events extend into the Caribbean with any significant frequency and amplitude. Evidence presented above indicates that there were positive Caribbean SST anomolies coincident with a 1969 El Niño. However, this circumstance precedes the reported onset of massive bleaching of the late 1980s and, interestingly, that El Niño was rated as less than `near moderate' in the Quinn *et al.* (1987) rating of El Niño strengths. There is no such indication of positive anomalies in the Caribbean for the very strong 1982/83 El Niño, and such indications are minimal to weak for the moderate El Niño of 1987, or strong one of 1972/73. There was no El Niño coincident with the 1990 bleaching event, however, an El Niño of indeterminate strength does seem to be in progress in 1991. Clearly, the effects of El Niño events have wide temporal and spatial variation, and few of recent record have had major SST effects in the Caribbean. The application of the Williams and Bunkley-Williams model to the explanation of 'preceding and following' bleaching events as resulting from an El Niño forcing of maximal annual temperatures past that of coral tolerance in three successive years, is faulted given the fact that no El Niño's of recent record, including the very strong and long 1982/83 event, have extended over three years.

However, any analysis of this type and of the types referenced herein, suffers from a lack of consistent, long-term data that are synoptic in time and space with observations of coral reef ecosystem health. Ideally, such data sets would not be restricted to temperature and would include such parameters as wind and current speed and direction, rainfall, salinity, light exposure, proxies for water column sediment load, pigment concentration and/or productivity, as well as water chemistry including nutrients and dissolved oxygen. Such data sets do not exist and can only be acquired by carefully implemented monitoring programs. As recommended by Elms (1991), if there is a clear public interest in understanding stresses on coral reef ecosystems, such monitoring programs should now be started.

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