

UNIVERSITY OF MIAMI

INCIDENCE OF BLEACHING AND DISEASE IN HERMATYPIC SCLERACTINIAN
CORALS OF BISCAYNE NATIONAL PARK

By

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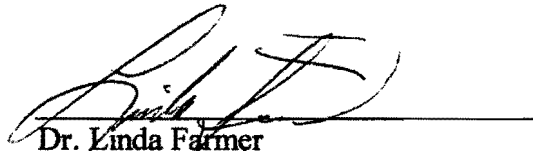
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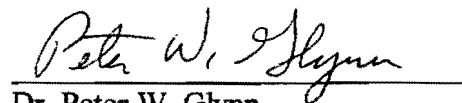
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ABSTRACT

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Incidence of Bleaching and Disease in Hermatypic Scleractinian Corals of
Biscayne National Park.

(April, 2000)

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The world's coral reefs generate large sums of income and provide a habitat for a wealth of diverse species, making them valuable economic and biological resources. Due to recent increases in the frequency of coral bleaching and disease, concern has developed over the health of coral reef ecosystems. This thesis had two objectives: (1) to determine whether mass bleaching events in the Florida Keys during the 1990's were related to high sea surface temperatures and (2) to establish baseline coral health and disease levels on the reefs of Biscayne National Park.

To determine whether the bleaching events were temperature related, known bleaching years were compared with both annual maximum temperatures and the annual number of bleaching index days. No statistically significant associations between elevated temperature and bleaching years were determined. However, a general trend was observed between bleaching events and an increased number of bleaching index days.

Reef surveys were conducted to establish the current levels of coral diseases and the general health of scleractinian corals of Biscayne National Park. The disease frequencies were variable among the reef sites, ranging from 0.0% to 3.7% infection. ✓ Two diseases were detected in the surveys: White Band Disease which was present in approximately 0.35% of surveyed colonies and Yellow Blotch Disease which had infected 1.1% of surveyed corals. Both diseases were most frequent in *Montastrea spp.*, which may suggest a reduced resistance to infection. The greater frequency of disease on the patch reefs of the carbonate platform, versus the barrier-bank reefs on the edge of the platform, was statistically significant and may be due to the greater volume of Hawk Channel water bathing the patch reefs. A majority of surveyed colonies were classified as healthy, although a considerable percentage (26.0%) exhibited signs of moderate to severe coral stress. Although only a small percentage (2.0%) of colonies were bleached, *Agaricia agaricites* composed 32.4% of these colonies. Approximately 3.3% of the surveyed colonies exhibited pale coloration (partial bleaching). These data will serve as baseline health and disease levels which may be used for comparison with future studies.

White Band Disease
Agaricia

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PREFACE

The world's coral reefs are an extremely valuable economic resource. For the human population in more than 100 countries (Epstein *et al.* 1998), these reefs are a vital source of both food and income (Carte 1996). Reef resources are especially important in many developing countries, supplying one quarter of the total fish catch (Bryant *et al.* 1998) and generating millions of fishery jobs (Roberts *et al.* 1998). Reefs supply income through the harvest of fish and other organisms, the excavation of building materials, the supply of biomedical and pharmaceutical resources, and through tourism (Carte 1996; Hoegh-Guldberg 1999). Tourism is presently a massive generator of income for numerous countries (e.g. the United States, Australia, and many Caribbean countries) and is continuing to grow in importance (Hoegh-Guldberg 1999). Additionally, coral reefs generate beach sand (Epstein *et al.* 1998) and act as barriers to protect developed coastal ^{not really} regions from the ravaging effects of storms, flooding, and waves (Jaap 1984; Jaap and Hallock 1990; Hoegh-Guldberg 1999).

Coral reef ecosystems also play important biological and ecological roles. Due to the immense biological diversity contained within them, coral reef ecosystems have been likened to an oceanic version of the tropical rain forest (Connell 1978). The most significant biological role of coral reefs is to provide a habitat for other reef-dwelling organisms (Jaap and Hallock 1990; Epstein *et al.* 1998). Additionally, coral reefs provide food for migrating fishes, birds, and marine mammals (Epstein *et al.* 1998) and act as nursery grounds for the juvenile stages of important commercial fishes (Jaap 1984).

The health of the world's coral reefs has experienced decline over the past several decades (Glynn 1996). The precarious situation of coral reefs has become an

international concern, and governments from many countries have begun to implement measures to protect and restore these ecosystems (Hoegh-Guldberg 1999). Currently, 50%-70% of the world's coral reefs are experiencing the direct impact of destructive anthropogenic activities such as eutrophication, increased sediment loading, pollution, mining, over-fishing, and direct physical injury (Simons 1993; Hoegh-Guldberg 1999). These damaging processes may also reduce both the coral organism's resistance to disease and its ability to recover from natural hazards (Epstein *et al.* 1998). Jokiel *et al.* (1975) demonstrated that corals may act as key indicators of community health because their responses to a disturbance (i.e. temperature changes) often parallel those of other reef organisms. In order to protect these valuable and vulnerable ecosystems, the current health of existing coral reefs must first be established.

TABLE OF CONTENTS

	<u>Page</u>
Abstract	
Acknowledgements	iii
Preface	iv
Table of Contents	vi
Chapter One – Coral Bleaching Events in the Florida Keys During the 1990's in Relation to Elevated Seawater Temperatures	1
Introduction	1
The Symbiosis	1
Causes of Coral Bleaching	2
Effects of Coral Bleaching	5
Recent Increase in Bleaching Frequency and Magnitude	6
Link Between Bleaching and Global Warming	7
Methods	13
Study Sites	13
Temperature Data Collection and Analysis	16
Results and Discussion	17
Chapter Two – Levels of Disease and General Condition of Hermatypic Scleractinian Corals of Biscayne National Park	26
Introduction	26
Background	26
Recent Elevations in Coral Disease Levels	26
Coral Diseases	27

Possible Explanations for Elevations in Disease Levels	29
Coral Diseases as Indicators	30
White Band Disease	31
Yellow Blotch Disease	33
Black Band Disease	35
The Purpose of this Study	35
Methods	37
Study Sites	37
Coral Disease and Health Data Collection	38
Results	39
Disease Levels	39
Colony Health	41
Bleached and Pale Colonies	41
Discussion	44
Disease Levels	44
Colony Health	49
Bleaching and Paleness	50
References	53

CHAPTER 1

CORAL BLEACHING EVENTS IN THE FLORIDA KEYS DURING THE 1990'S IN RELATION TO ELEVATED SEAWATER TEMPERATURES

INTRODUCTION

The Symbiosis

Hermatypic corals, also referred to as reef-building or stony corals, belong to the order Scleractinia and host large numbers of zooxanthellae (dinoflagellate microalgae) within their tissues (Glynn 1993, 1996). The relationship between these photosynthetic algae and their animal hosts has been identified as a symbiotic mutualism, both organisms reaping benefits from the association (Hoegh-Guldberg 1999). Zooxanthellae contribute to the host coral's success most significantly by providing a majority (60%) of the coral's nutrient intake and by enhancing calcification, the deposition of the calcium carbonate skeleton (Barnes and Chalker 1990; Glynn 1991; Muller-Parker and D'Elia 1997). Without the aid of zooxanthellae, coral skeletal growth rates would be greatly reduced, thus limiting the formation of reef frameworks (Glynn 1991). The endosymbiotic algae benefit from the association by harvesting essential nutrients including ammonia and phosphate from the metabolic waste products of the host coral (Hoegh-Guldberg 1999). *nutrient recycling*

The term "coral bleaching" refers to two processes: the active displacement of the zooxanthellae from the host coral and/or a "paling" of the zooxanthellae as the result of a reduction in photosynthetic pigment concentrations within the algal tissue (Hoegh-Guldberg and Smith 1989; Glynn 1993). Approximately 60-90% of the endosymbiotic algae may be expelled from a coral colony during bleaching, and individual algae may

lose 50-80% of their photosynthetic pigments (Glynn 1996). The characteristic pale or stark-white appearance that results from this response make it possible to visually identify a bleached specimen (Fig. 1). This distinctive coloration results from the reduced amounts of algal pigments and increased visibility of the calcium carbonate skeleton (Glynn 1991, 1993).

diffuse multiple
as an example
since it is not
a coral!

Causes of Coral Bleaching

As coral bleaching is associated with a variety of anomalous environmental parameters, it is considered a generalized response to physiological stressors of the coral animal (Brown 1997). Specifically, extreme temperatures, reduced salinity, elevated solar irradiance including photosynthetically active radiation (PAR) and ultra violet radiation (UVR), aerial exposure, increased sedimentation, pollution, xenobiotics (foreign chemical compounds), and epizootics (high frequency of disease) have been established as correlates of bleaching events (for references, see Glynn 1996). In addition, both field and laboratory studies have demonstrated that bleaching can be induced by a bacterium (Kushmaro *et al.* 1996). Bleaching events have occurred on both small, localized scales (e.g. portions of a single reef) and on large scales (e.g. "mass bleaching" over hundreds or thousands of square kilometers) (Glynn 1996; Hoegh-Guldberg 1999).

Bleaching is a
symptom of stress.

While all of the factors listed above may be linked to local bleaching events, the parameters that warrant the greatest plausibility as inducers of mass bleaching events are elevated temperatures and UVR (Glynn 1993). These two factors are suspected because they experience changes over a larger geographic area than do the other bleaching inducers (Glynn 1993). Temperature and UVR have both been experimentally shown to induce coral bleaching (for references, see Glynn 1993, 1996; Lesser *et al.* 1990). High

Most common
association
not pure I agree
with "plausibility"

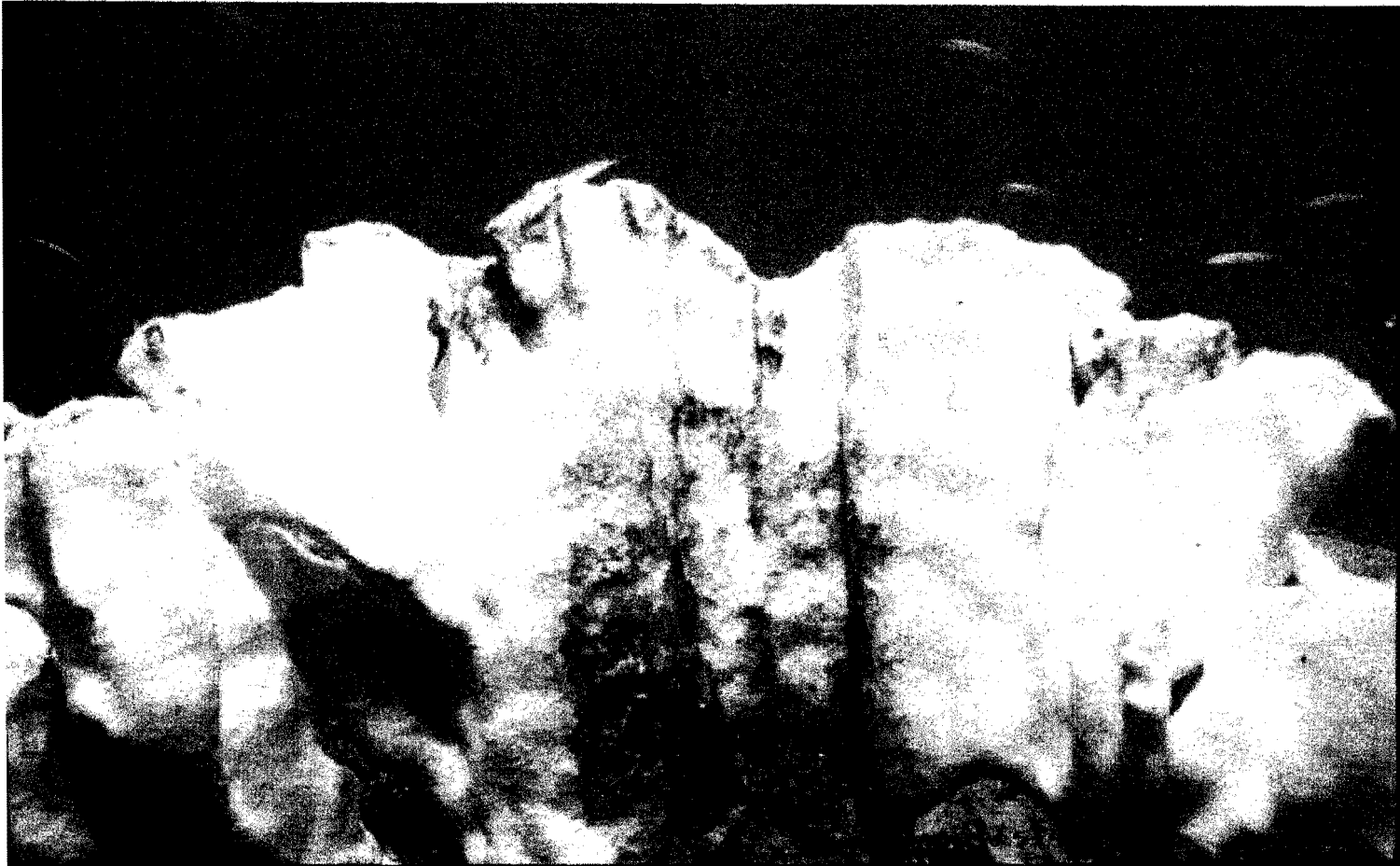


Figure 1. A bleached coral colony in the Florida Keys. Photo by S. Miller. Source: OAR/National Undersea Research Program (NURP).

sea surface temperatures (SSTs) have been associated with all cases of large-scale mass bleaching events (Glynn 1993; Goreau and Hayes 1994). It has been observed that corals tend to bleach primarily on their upper surfaces, which suggests that exposure to UVR may be involved in the initiation of bleaching (Jokiel and York 1982; Siebeck 1988; Lesser *et al.* 1990). However, there have been no reported incidents of mass bleaching episodes due to elevated UVR levels alone (Wilkinson *et al.* 1999). Thus, it is unlikely that UVR is the principal causal factor in mass bleaching (Wilkinson *et al.* 1999). Rather, high UVR levels associated with doldrum-like conditions (lack of strong winds, cloudless skies, calm water, and low turbidity) may act synergistically with elevated temperatures to intensify bleaching (Glynn 1993; Wilkinson *et al.* 1999). Coral bleaching frequently occurs during the summer months when temperature and solar radiation reach their maximum levels (Glynn 1996).

Corals require a specific temperature range for survival (18°C to 30°C) (Vernon 1986). Tropical scleractinian corals are often found within close proximity of their maximum temperature limits; thus, even a slight increase in water temperature can have damaging effects on the coral (Hoegh-Guldberg and Smith 1989; Glynn 1996; Epstein *et al.* 1998). The correlation between high water temperatures and events of mass coral bleaching and mortality (Glynn 1993; Goreau and Hayes 1994; Brown 1997; Hoegh-Guldberg *et al.* 1997; Winter *et al.* 1998) has led most researchers to believe that thermal stress is the primary cause of these occurrences (Hoegh-Guldberg 1999). It has been experimentally determined that bleaching may be induced by short-term (1 to 2 days) extreme temperature increases (4-5°C over the mean summer maximum temperature) or by extended periods (several weeks) of small temperature elevation (1-2°C over the mean

summer maximum temperature) (for references, see Jokiel and Coles 1990; Goreau and Hayes 1994; Glynn 1996). The National Oceanographic and Atmospheric Administration (NOAA) has developed the "hot spot" program which uses satellite-derived SST data to predict bleaching events (Goreau *et al.* 1993; Goreau and Hayes 1994; Strong *et al.* 1997). The program (which has been quite accurate in its predictions) identifies pools of ocean water greater than 1°C over the monthly mean temperature and then estimates the location and temporal period of possible future mass bleaching events (Strong *et al.* 1997).

Effects of Coral Bleaching

Bleaching stimulates several physiological effects in the coral animal. The coral is, in effect, starving without its energy-supplying symbionts (Wilkinson *et al.* 1999). Levels of protein, lipid, and carbohydrate decrease (Glynn 1993), respiration rates increase, skeletal growth slows or ceases (Goreau and Macfarlane 1990), tissue death may occur, and the corals show a decreased capability to shed sediment and recover after injury (Glynn 1996). In addition, the coral's reproductive capacity may be compromised, thus reducing the recruitment of planulae onto the reef (Glynn 1990; Jokiel and Coles 1990; Szmant & Gassman 1990).

If the environmental stress that causes bleaching is neither severe nor long-lived, the coral will most likely recover (Oliver 1985; Gates 1990; Glynn 1993, 1996). The term "recovery" refers to the re-population of the lost zooxanthellae and/or pigment (Fitt *et al.* 1993). According to Fitt *et al.* (1993), recovery most likely occurs from reproduction of the algae that remain in the tissues after bleaching. Full recovery tends to occur when one of the following has taken place: (1) incomplete bleaching, a portion of

the algal symbionts remain in the tissues (Hoegh-Guldberg and Smith 1989; Porter *et al.* 1989); (2) slight thermal stress is present for an intermediate duration, less than 3 months (Lasker *et al.* 1984; Sandeman 1988); and (3) coral recovery occurs within a relatively short period of time, weeks to months (Hoegh-Gulberg and Smith 1989; Szmant and Gassman 1990).

Conversely, if the bleaching is severe and lasts for an extended period, then recovery is unlikely and mass coral mortality may result (Glynn 1996). An increase in the abundance of fleshy macroalgae has been observed to follow the reduction in coral cover that is associated with mass coral mortality (de Ruyter van Stevenick and Bak 1986; Liddell and Ohlhorst 1986; Hughes *et al.* 1987; Done 1992). Also, declines in species richness and diversity often accompany coral cover loss (Porter and Meier 1992). These changes may lead to major alterations in the structure of the ecosystem and severely affect the success of other reef biota (Glynn 1996). Jokiel *et al.* (1975) found that thermally-induced coral injury (i.e. bleaching) was reflected in the reduced diversity and biomass of other reef organisms. In the most extreme case of prolonged thermal stress, a complete disintegration of the reef structure would occur (Glynn 1996).

Recent Increase in Bleaching Frequency and Magnitude

During the 1980's, both the frequency and magnitude of reported bleaching incidents increased substantially in comparison to prior records (for references, see Glynn 1996). There are very few officially recorded bleaching episodes prior to 1979 (Hoegh-Guldberg 1999), yet over the twelve-year span from 1979-1990, more than sixty bleaching events were formally recorded (Glynn 1993). Not only had the bleaching events become more prevalent, they had also spread over a much larger spatial scale

(Fig. 2) and affected a greater number of coral species (Glynn 1993; Goreau *et al.* 1993).

This point is exemplified by the bleaching event of 1998 which was unprecedented in both its spatial magnitude and severity (Fig. 3) (Strong *et al.* 1998; Harvell *et al.* 1999; Wilkinson *et al.* 1999). The unprecedented frequency and extent of these bleaching events, along with the knowledge of the correlation between high temperature and bleaching, generated a good deal of speculation concerning a possible causal relationship between global warming and bleaching (Glynn 1996).

An examination of the historical record indicates that the apparent increase in bleaching frequency and magnitude due to temperature stress has begun only in the recent past (Glynn 1991). One must consider, however, that the escalation in reported bleaching events could also be attributed to an increase in awareness of bleaching in the scientific community and more frequent observations (Glynn 1993). Glynn (1993), however, points out that this is an improbable scenario when it is considered that only nine bleaching events were recorded during two decades (1960-1979) of intensive research on coral reefs.

Link between Bleaching and Global Warming

It is imperative that the underlying cause of the increased frequencies of mass bleaching and mortality be determined. Two general hypotheses have been generated to account for this increase: natural variations in the Earth's climate and global warming (Glynn 1993). If the frequency and severity of bleaching episodes decreases within this decade, then the first hypothesis is probably the correct one (Glynn 1993). However, the apparent global warming trend (Fig. 4) is becoming more of a probability than mere speculation. Over the last century, a highly significant warming trend of more than 2°C

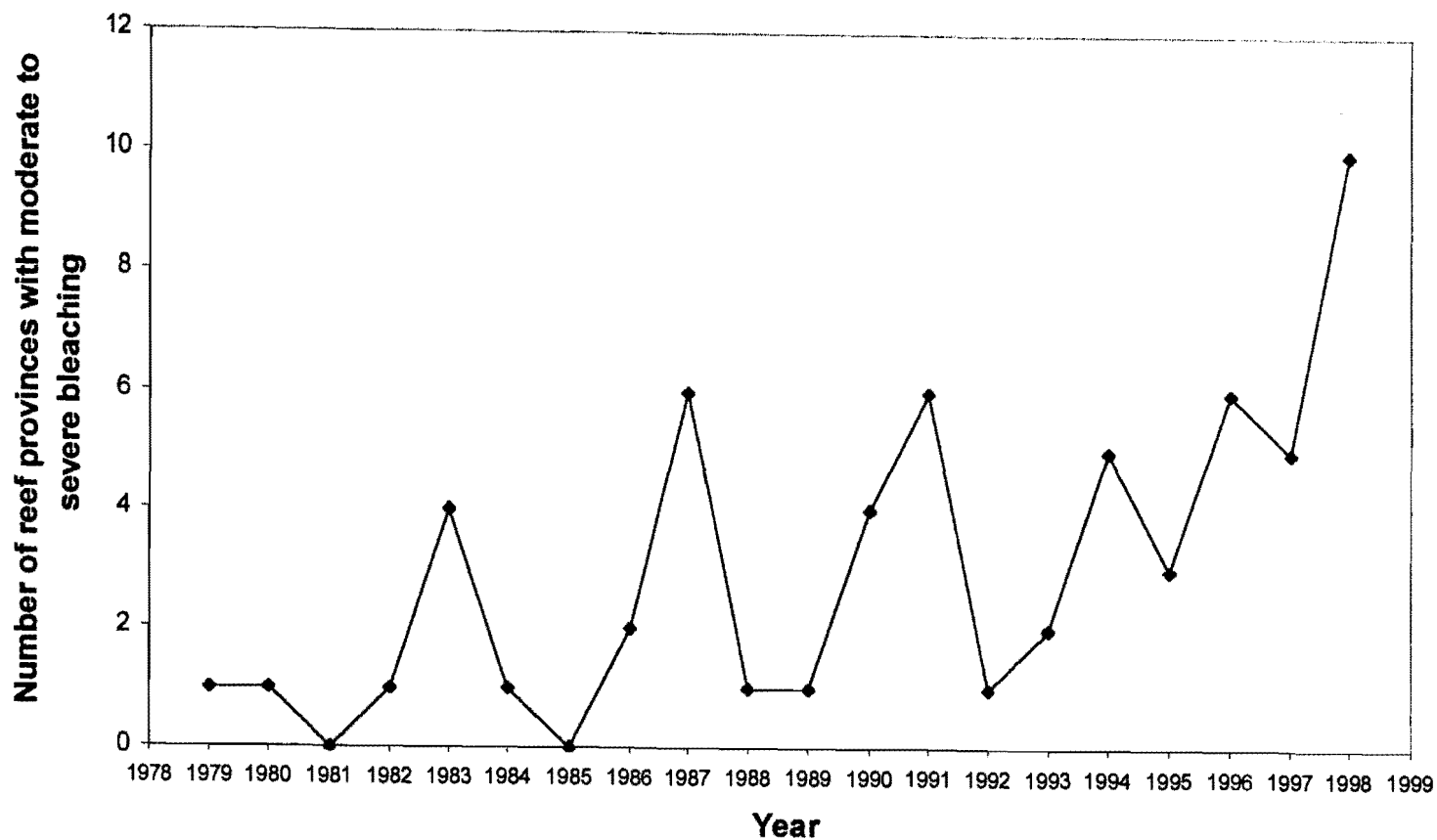


Figure 2. Number of reef provinces bleaching since 1979. (Graph modified from Goreau and Hayes (1994) with data added for 1992 onwards.) Source: Hoegh-Guldberg (1999).

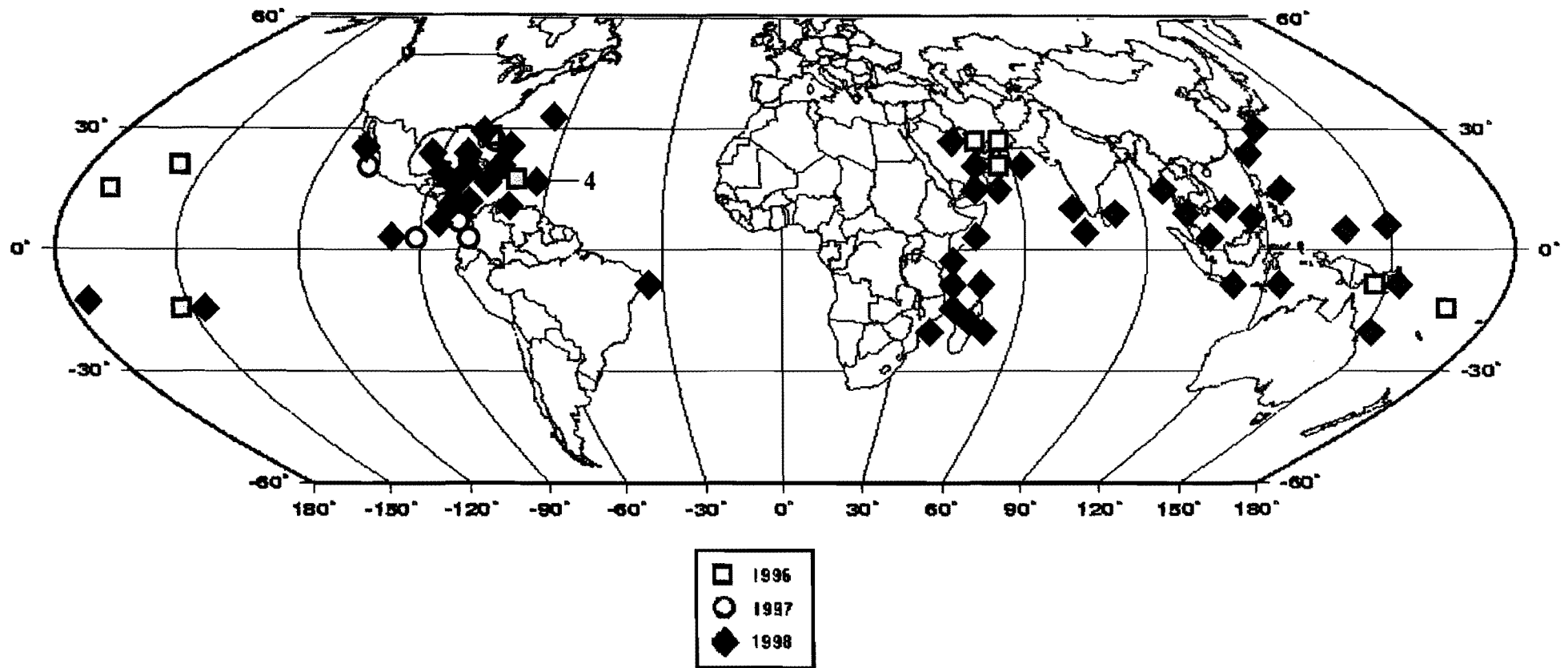


Figure 3. Global distribution of coral reef bleaching events for 1996-1998. Note the disproportionate number of bleaching events that occurred during 1998. Source: Peter Glynn, RSMAS.

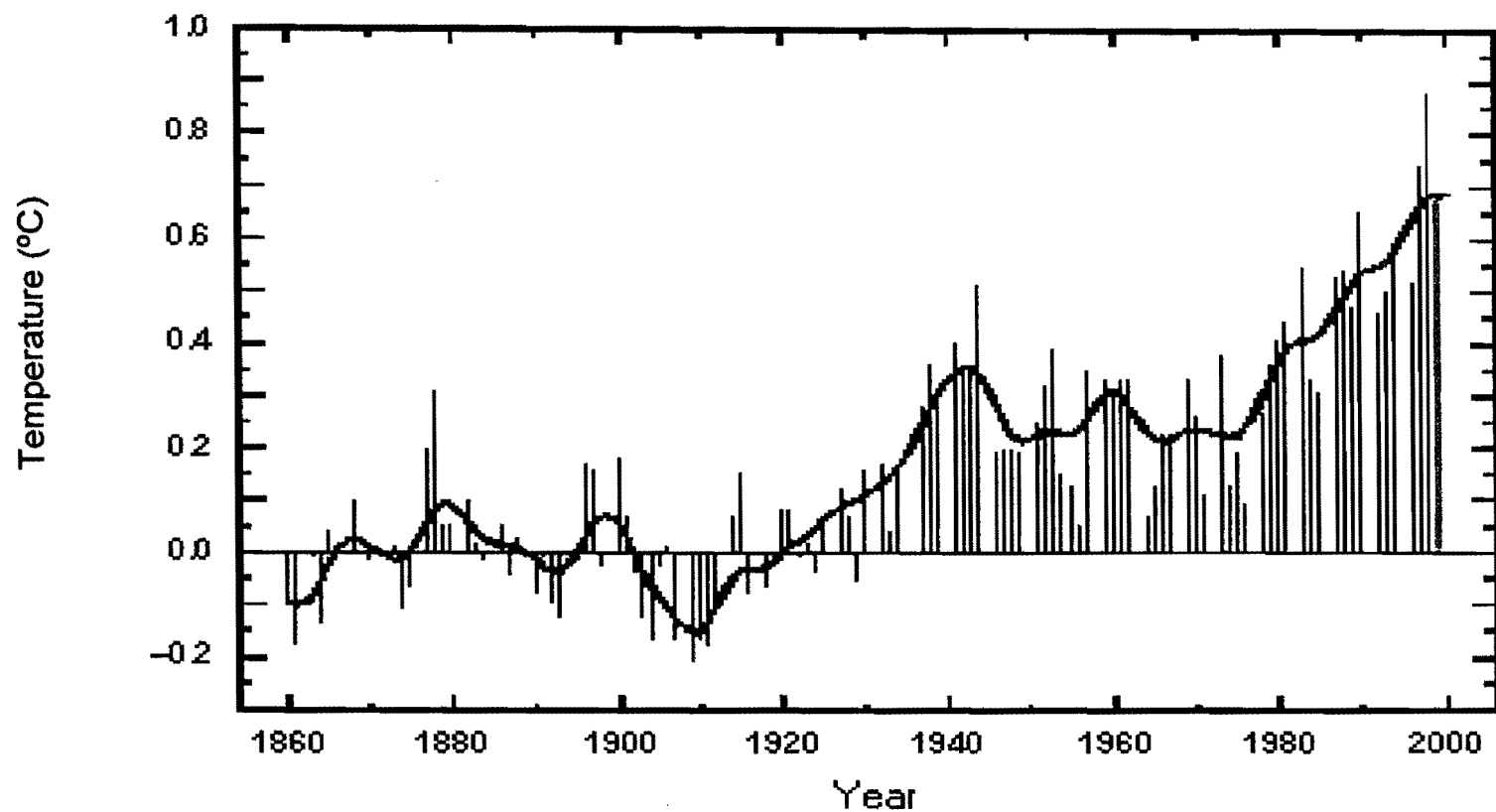


Figure 4. Global mean annual temperature over the past 140 years. A long-term trend line is shown. The increase in mean temperatures is apparent with 1998 being the warmest year on record. Source: Hadley Center.

per 100 years has been detected in the tropical regions of the world's oceans (Table 1) (Cane *et al.* 1997; Hoegh-Guldberg 1999). The Intergovernmental Panel on Climate Change (IPCC) has determined that a global temperature increase of 0.3°C to 0.6°C has already taken place (IPCC 1995). The results from the most recent climate model released from the Hadley Center predict a 2°C increase in seawater temperature over the next 50 years as a result of global warming (Hadley Center 1998). As has been previously addressed, an increase of 2°C could have drastic effects on coral vitality. Hoegh-Guldberg (1999) examined the results of four Global Circulation Models and found that all forecast the continual warming of tropical SSTs.

These predicted temperature elevations appear to be reflected in the increasing frequency of bleaching events; although, this remains a controversial subject (Glynn 1991). For example, the 1998 bleaching event corresponded with the highest global SST (Fig. 4) and strongest El Niño-Southern Oscillation (ENSO) event ever recorded (Wilkinson *et al.* 1999). This severe bleaching event could simply have been caused by a combination of meteorological and circulation conditions that resulted in the anomalous temperatures; however, the recent elevated bleaching frequencies have led some researchers to speculate that global warming may have been the underlying cause (Wilkinson *et al.* 1999).

If global warming is actually occurring, the corresponding temperature elevations would have detrimental effects on coral reefs (Wilkinson *et al.* 1999), including an increase in both the frequency and severity of bleaching episodes (Glynn 1993; Hoegh-Guldberg 1999). Glynn (1993, 1996) assumes that global warming is indeed occurring and examines the possible consequences of this assumption. His predictions regarding

Table 1. Rates of warming in tropical oceans for period 1981-99. Rates determined from regressions done on Integrated Global Ocean Services System (IGOSS) nmc blended weekly sea surface temperature data obtained from data sets available at the Lamont Doherty Earth Observatory server (<http://rainbow.ldgo.columbia.edu/>). Seasonal variability within the data was removed by applying a 12-month moving-point average before the regression analysis. Source: Hoegh-Guldberg (1999).

GBR, Great Barrier Reef

Locality	Position	Rate (°C per 100 years)	Significance of trend	Other data
Jamaica	17.5°N, 76.5°W	2.29	< 0.001	2.53, Winter <i>et al.</i> (1998)
Phuket	7.5°N, 98.5°W	2.3	< 0.001	1.26, Brown (1997)
Tahiti	17.5°S, 149.5°W	1.44	< 0.001	
Rarotonga	21.5°S, 159.5°W	2.27	< 0.001	
Southern GBR	23.5°S, 149.5°E	2.54	< 0.001	
Central GBR	18°S, 147.5°E	2.59	< 0.001	
Northern GBR	11°S, 143°E	0.47	< 0.001	

the effects of thermal stress include mass coral mortality, an increase in corallivore and bioeroder populations, the slowing or halting of coral growth, and the replacement of corals by other benthic taxa such as macroalgae and suspension feeders. Accompanying the elevated seawater temperatures (Fig. 5a) would be a rise in sea level (Fig. 5b) (IPCC 1995; Glynn 1996). Glynn (1996) predicts that this sea-level rise would produce high coral mortality between 20°-30°N latitude due to the continuous warming of this zone, the "drowning" of high-latitude and deep water reef sites, and the "pole-ward expansion" of reefs toward more ideal environmental temperatures. It is a general consensus that coral reefs lack the capacity to evolve rapidly enough to keep pace with these predicted climatic changes (Jokiel and Coles 1990; Glynn 1993, 1996; Hoegh-Guldberg 1999).

In this study, mass bleaching events that occurred in the Florida Keys during the 1990's were examined in relation to seawater temperatures. The purpose of this study was to determine whether a correlation between water temperatures and mass bleaching events exists in a local setting.

METHODS

Study Sites

The temperature data were collected from reefs located in Biscayne National Park (BNP). Situated in southeast Florida, BNP encompasses a portion of the middle and lower sections of Biscayne Bay (Fig. 6) (Hudson *et al.* 1994). The park is bordered on the east by Hawk Channel and extends westward to the seaward edge of the Florida reef tract. Biscayne Bay is a shallow lagoon (maximum depth 4 m) that connects the Florida coast with the Atlantic Ocean through a variety of shoals, passes, and channels (Lee and

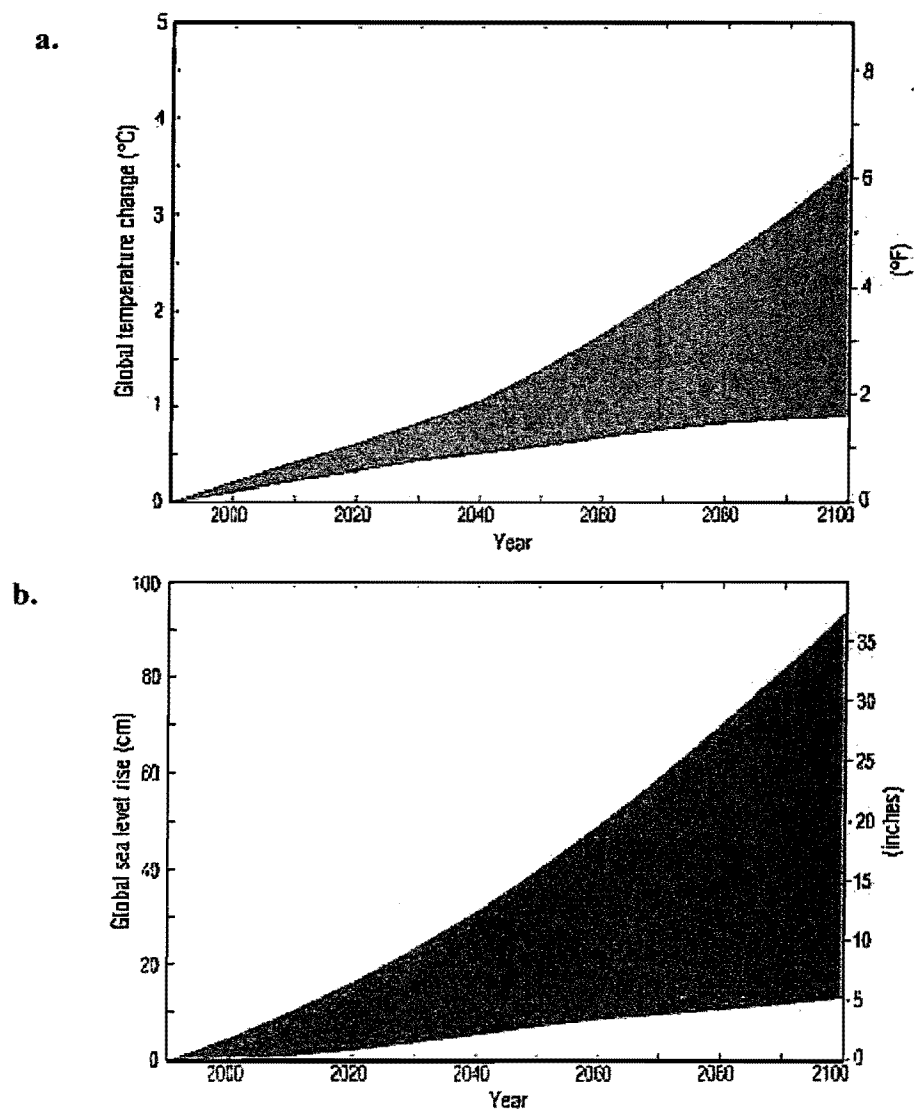


Figure 5. International Panel on Climate Change (IPCC) predictions as a result of global warming. (a.) the possible range of global temperature increase for the period 1990-2100. (b.) the possible range of global sea level rise for the period 1990-2100.

Source: GCRI (1999).

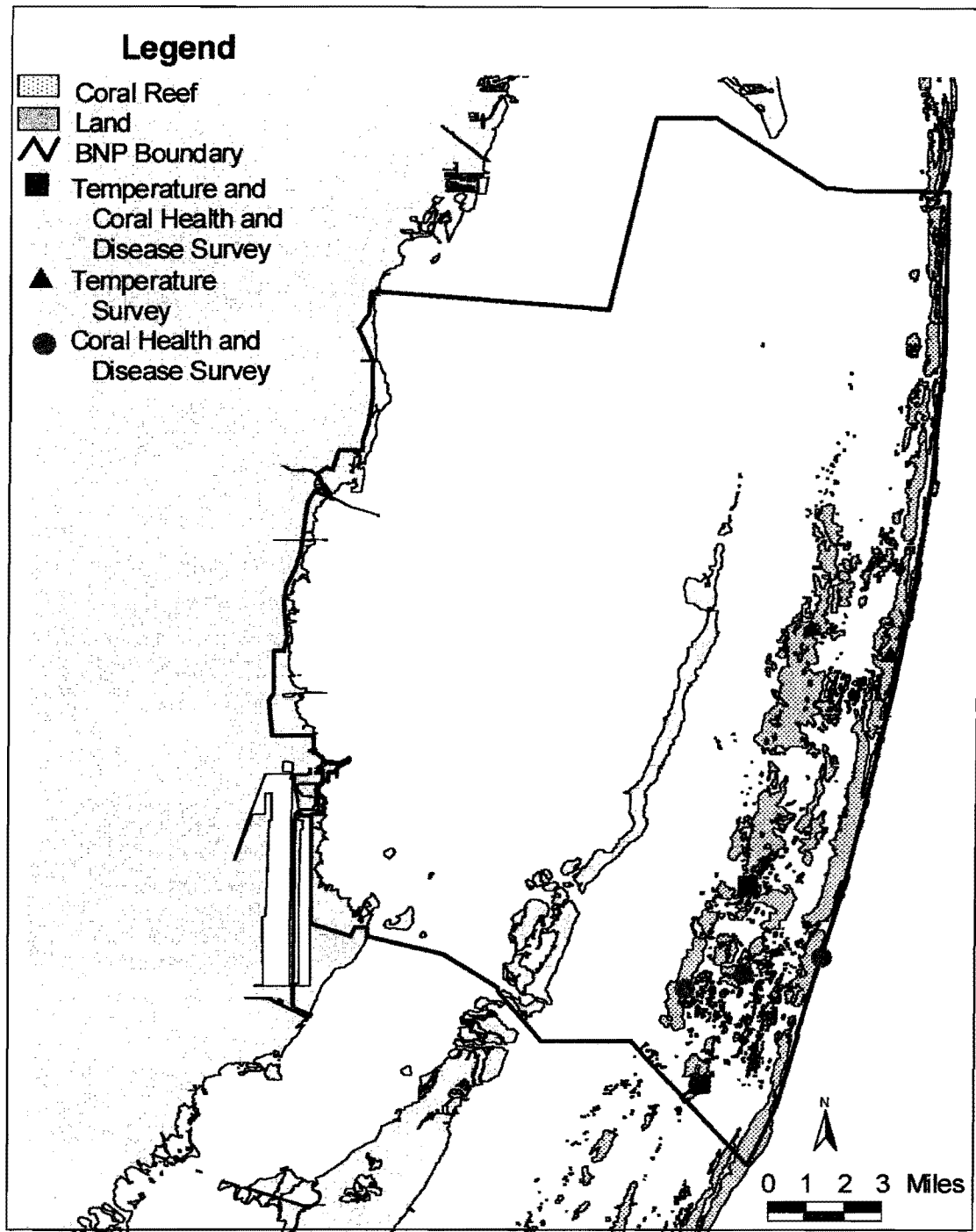


Figure 6: Location of the study sites in Biscayne National Park.

Sites where temperature data were collected are shown as purple triangles. Sites where coral health and disease surveys were conducted are shown as green circles. Sites where both temperature data were collected and coral health and disease surveys were conducted are shown as red squares.

Rooth 1976). The multitude of patch and bank-barrier reefs located within BNP composes the northernmost tip of the Florida reef tract (Jaap 1984).

Four reef sites were chosen for the collection of temperature data: Triumph Reef, Bache Shoal Reef, Ball Buoy Reef, and Alina's Reef (Fig. 6). Triumph Reef (25° 28.6'N, 80° 06.7'W) is a bank-barrier reef situated along the western boundary of the Florida reef platform. Bache Shoal Reef (25° 29.2'N, 80° 8.5'W) is a smaller shallow patch reef that lies west of Triumph Reef and is situated on the western edge of the reef platform. Ball Buoy Reef (25° 19.2'N, 80° 11.0'W) lies further south and is one of the most westward lying bank-barrier reefs in this area. Finally, Alina's Reef (25° 23.5'N, 80° 09.9'W) is a shallow patch reef located on the western side of the reef platform. This reef lies mid-way between the northern (Ball Buoy Reef) and southern (Triumph, Bache Shoal Reefs) study sites.

Temperature Data Collection and Analysis

It has been both experimentally determined and naturally observed that coral bleaching is initiated by temperature elevations $\geq 1^{\circ}\text{C}$ above the mean monthly maximum temperature (MMMT) during summer months (e.g. Coles *et al.* 1976; Goreau *et al.* 1993; Goreau and Hayes 1994; Brown 1997; Jones *et al.* 1997; Winter *et al.* 1998). This bleaching threshold will hereafter be referred to as the "bleaching index." Several aspects of the temperature data were examined to assess whether temperature may have played some role in causing the mass bleaching events.

Throughout the previous decade (1990-1999), thermistors were moored at each of the four reef sites. Hourly temperature data were collected over a ten-year period (1990-Bache Shoal Reef. Some exceptions in this sampling regime occurred due to mechanical

malfunction and data retrieval periods. To determine whether a link existed between high seawater temperature and bleaching events, two aspects of the environmental temperature were examined, the annual maximum temperature and the annual number of bleaching index days for each year.

The temperature data points from all four of the reef sites were combined into one database. The annual maximum temperature (Table 2) is the highest temperature that occurred over the course of a particular year. Daily temperature maxima were used to generate a long-term (i.e. averaged over the decade) MMMT for each of the summer months, May through October (Table 3). A monthly bleaching index (1°C above the MMMT) was calculated (Table 3). The number of bleaching index days (i.e. days in which the temperature reached or surpassed the bleaching index) was identified for each year (Table 2). The resulting dates were compared with the years of recorded mass bleaching in the Florida Keys during the past decade (1990-1999). The documented mass bleaching years included 1993 (Goreau *et al.* 1997), 1995 (McGrath and Smith 1998), 1997 (BNP, personal communication; Wilkinson 1998a; Hendee 1999), and 1998 (Strong *et al.* 1998; Wilkinson 1998a; Hendee 1999). Because the reefs of BNP make up the northern portion of the Florida reef tract, all mass bleaching events that occurred in the Florida Keys also occurred in BNP.

RESULTS AND DISCUSSION

Bleaching events occurred in three (1995, 1997, 1998) out of the four years with the highest annual maximum temperatures (1991, 1995, 1997, 1998) (Fig. 7). Bleaching events did not occur in three (1992, 1994, 1996) out of the four years with the lowest

Table 2. Annual maximum temperatures and numbers of bleaching index days for the years 1990-1999. The annual maximum temperature is the highest temperature that occurred during a specific year. Bleaching index days are those days in which the corresponding monthly bleaching index temperature was reached or exceeded.

Year	Max. Temperature (°C)	No. of Bleaching Index Days
1990	31.85	50
1991	33.12	57
1992	30.8	3
1993	31.22	14
1994	30.58	25
1995	32.03	42
1996	31.33	13
1997	32.13	42
1998	32.3	94
1999	31.76	37

Table 3. Mean monthly maximum temperatures (MMMTs) and bleaching indices for the months May-October. MMMTs are averages over the 10-year period. Bleaching index = MMMT + 1°C.

Month	MMMT (°C)	Bleaching Index (°C)
May	27.49	28.49
June	29.18	30.18
July	30.19	31.19
August	30.35	31.35
September	29.65	30.65
October	27.83	28.83

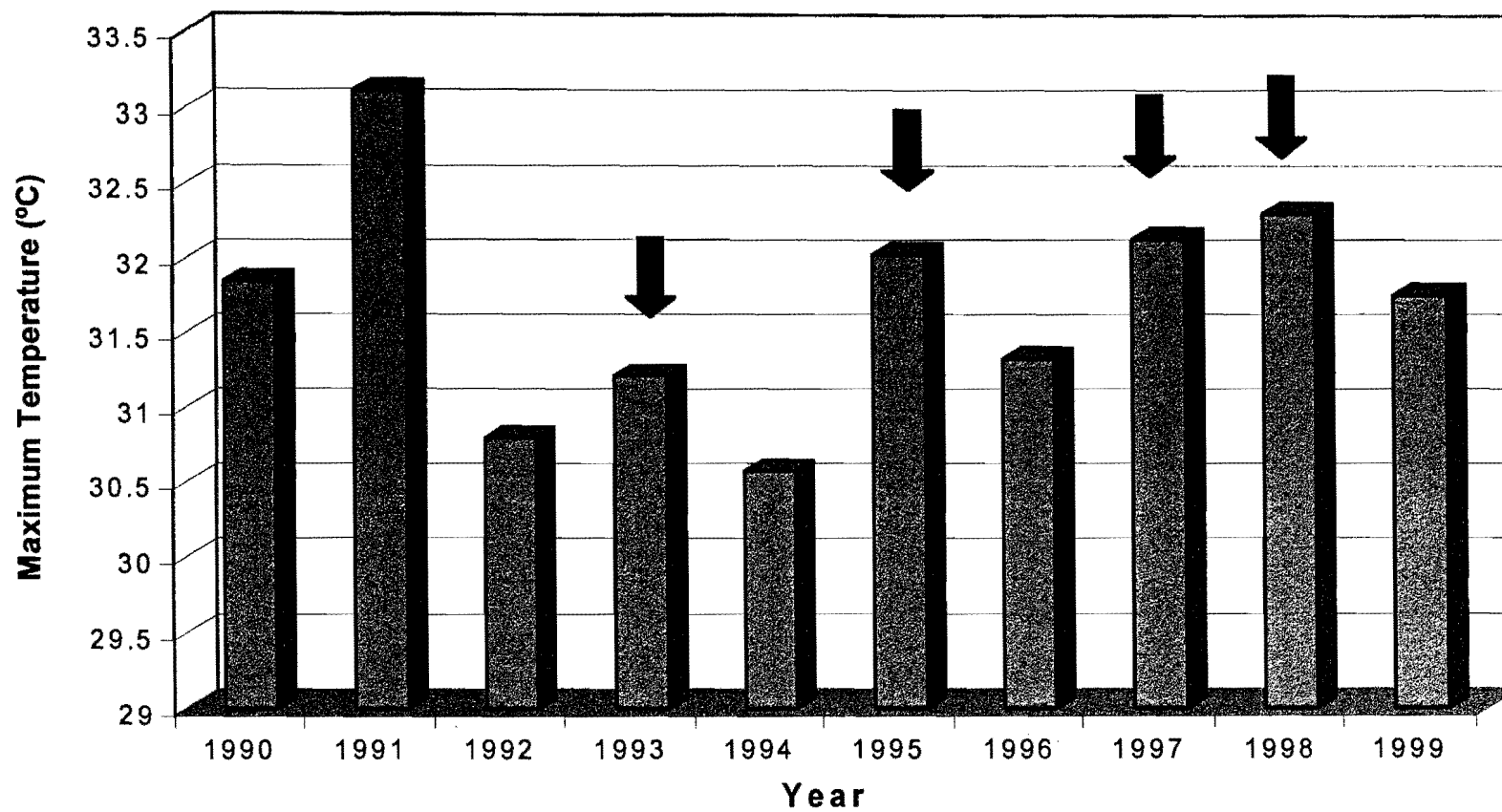


Figure 7. Annual maximum temperatures for the period 1990-1999. Bleaching years are indicated by arrows.

annual maximum temperatures (1992, 1993, 1994, 1996). The mean bleaching year maximum temperature (31.92°C) was just slightly higher than the corresponding mean for non-bleaching years (31.57°C) (Fig. 8). However, the annual maximum temperatures were not significantly different between bleaching and non-bleaching years (student's t-test, $p > 0.05$). Figure 9 shows the total number of bleaching index days that occurred within each year. The mean number of bleaching index days was higher for bleaching years (48 days) than for non-bleaching years (31 days) (Fig. 10); although, the total number of bleaching index days occurring during bleaching years was not statistically different from the number occurring during non-bleaching years (student's t-test, $p > 0.05$).

The results of this study suggest that neither of the temperature parameters examined was obviously related to bleaching events. Although this seems to suggest that no relationship existed between sea surface temperatures and bleaching, the statistics may be the result of an insufficient data set (only 10 years were available with corresponding temperature data). However, a general trend can be identified with respect to a higher number of bleaching index days occurring in bleaching years (Fig. 10). This suggests that temperature played some role in causing the mass bleaching in the Florida Keys. However, a study over an extended temporal scale is necessary to see if a significant trend exists. The measurement of additional parameters would have provided more information on the potential causes of the bleaching. Specifically, measuring PAR and UVR would have made it possible to examine with the elevated temperatures to cause the mass bleaching events.

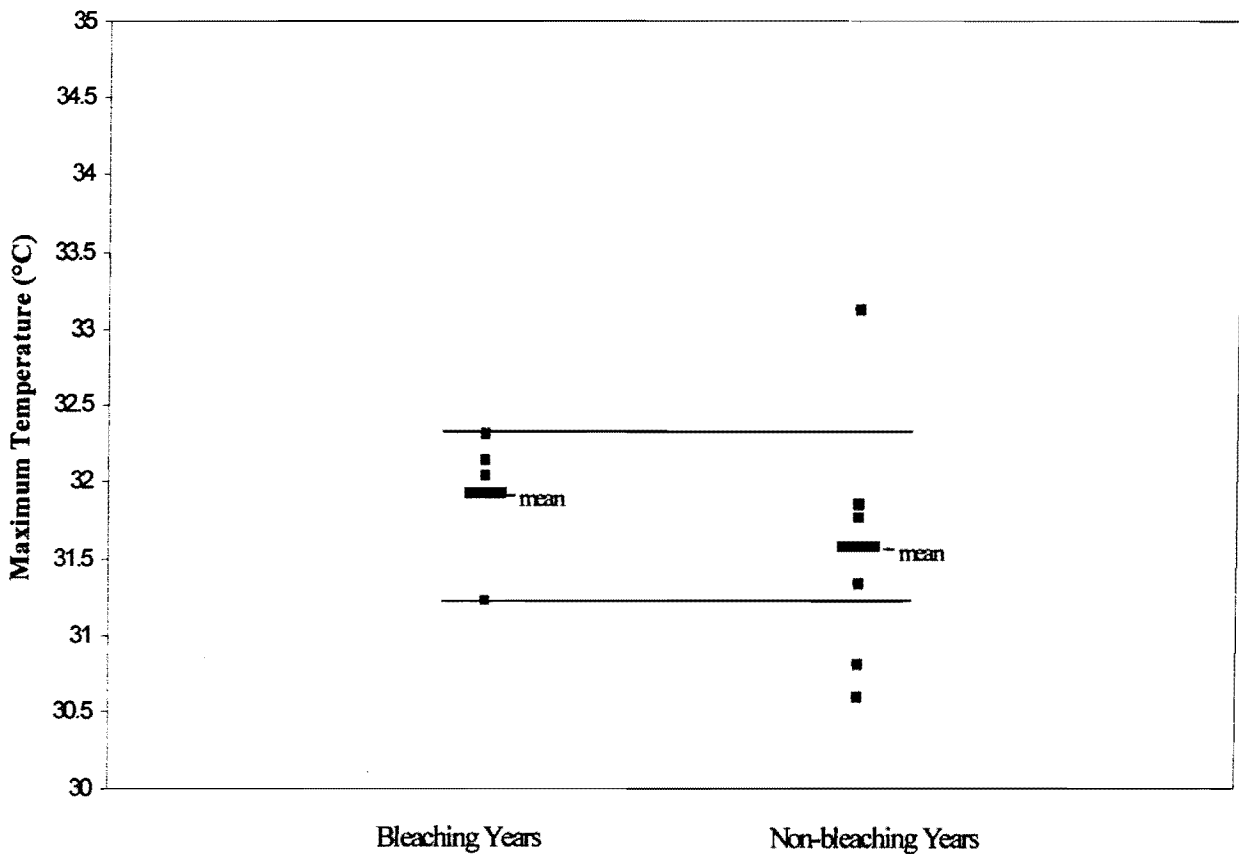


Figure 8. Annual maximum temperatures for bleaching and non-bleaching years for the period 1990-1999. Bleaching years were 1993, 1995, 1997, and 1998. Non-bleaching years were 1990, 1991, 1992, 1994, 1996, and 1999. The horizontal bars represent the mean annual maximum temperature. It is apparent that the mean maximum temperature for the bleaching years (31.92°C) is slightly higher than for the non-bleaching years (31.57°C); although, the difference between the two means is not statistically significant. The horizontal lines indicate the overlap between bleaching and non-bleaching years.

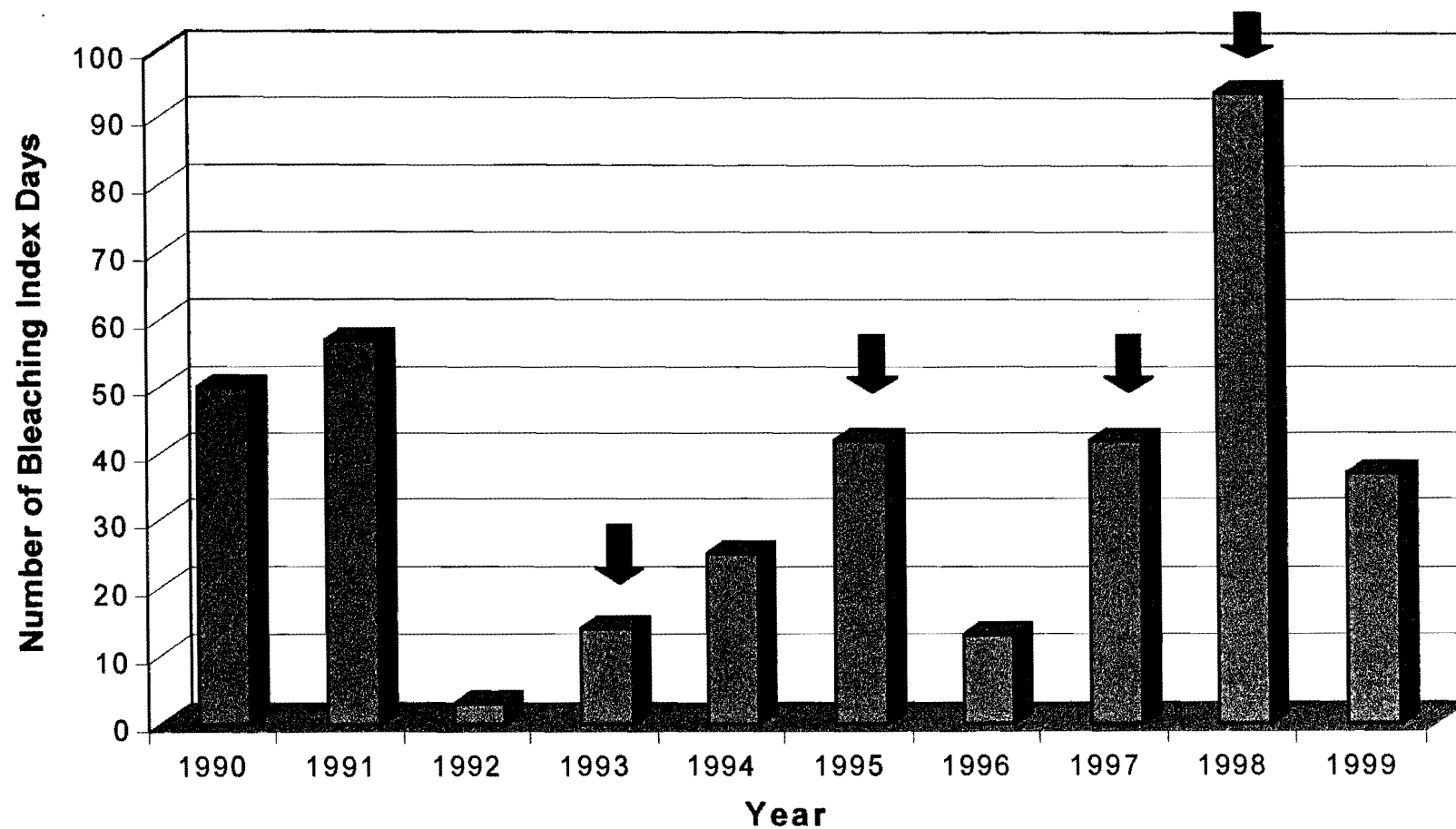


Figure 9. Annual number of bleaching index days for the period 1990-1999. Bleaching years are indicated by arrows.

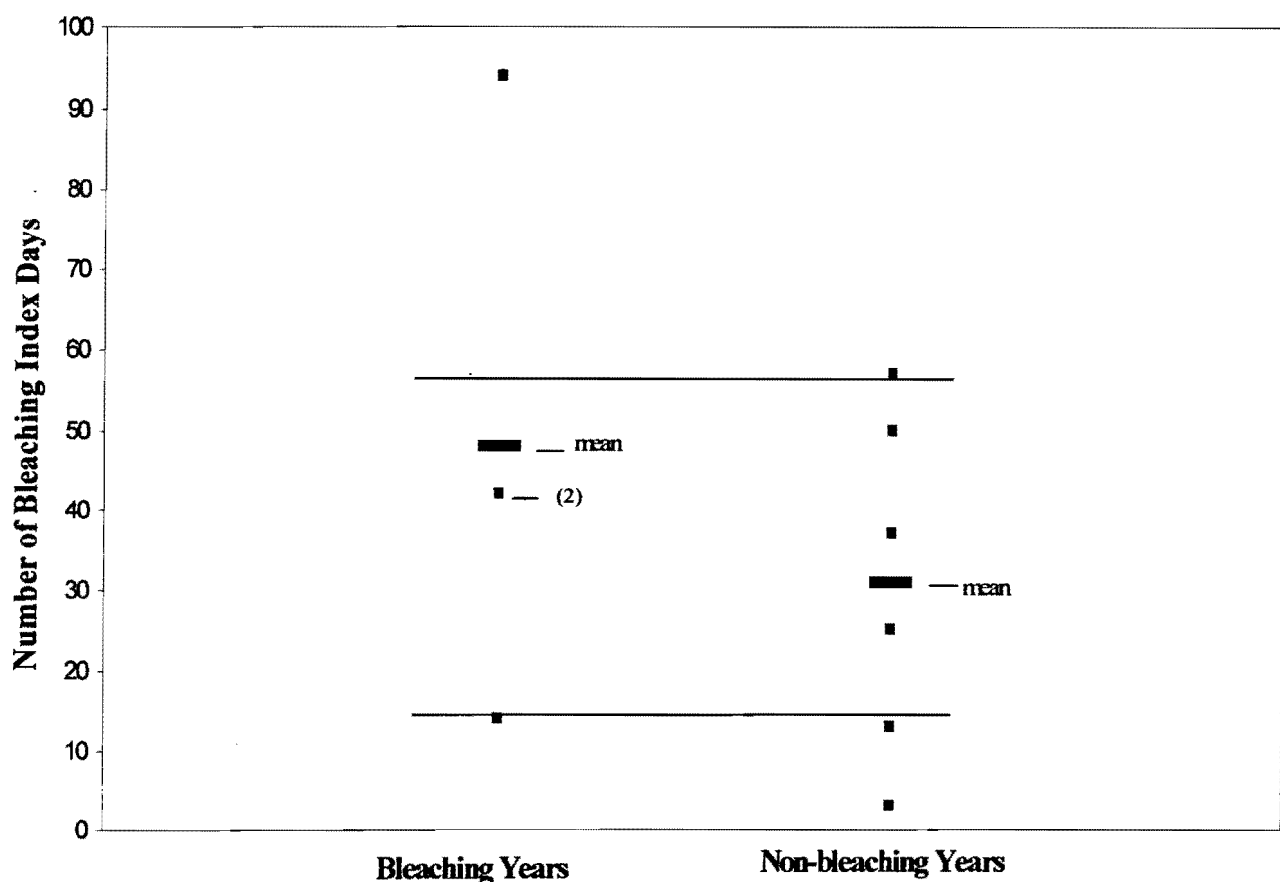


Figure 10. Number of bleaching index days for bleaching and non-bleaching years during the period 1990-1999. Bleaching years were 1993, 1995, 1997, and 1998. Non-bleaching years were 1990, 1991, 1992, 1994, 1996, and 1999. The horizontal bars represent the mean number of bleaching index days. Note that the mean number of index days during bleaching years (48 days) was higher than for the non-bleaching years (31 days); although, the difference between the two means is not statistically different. The horizontal lines indicate the overlap between bleaching and non-bleaching years.

Although a continuous decadal temperature record (more than 280,000 data points) was available and analyzed in this study, the lack of accessible bleaching data, published or otherwise, was restricting. While the years of bleaching occurrence were readily available, and most accounts were associated with a particular month or months, the specific day of the onset of bleaching remained unspecified. This is most likely because mass bleaching, although it occurs simultaneously over an expansive area, may begin at different times in separate localities as a result of local temperature variation. Also, not all reef sites are observed on a daily basis, thus, a confirmed initial bleaching date would not be available for these areas. Had the initial bleaching dates been established for BNP or even the northern Florida Keys, a smaller-scale (daily rather than yearly) analysis could have been performed. It would have been possible to examine the temperature trends in the days and weeks before bleaching was initiated.

The proposed relationship between elevated seawater temperature and bleaching would predict that mass bleaching events in the future may have drastic effects on the coral reefs of the Florida reef tract. If global warming persists, SSTs will continue to rise and mass bleaching events will increase in both severity and magnitude. It has been observed thus far that reefs of the Caribbean usually recover following bleaching events (e.g. Gates 1990; Fitt *et al.* 1993). However, once SSTs surpass critical temperatures due ostensibly to global warming, mass coral mortality would result. Many instances of temperature-related mass coral mortality have been documented on reefs (e.g. Glynn 1984; Glynn 1990; Warwick *et al.* 1990; Guzmán and Cortés 1992; Wilkinson *et al.* 1999). Studies have shown that mass coral mortality may result in a shift from coral-dominated to algal-dominated communities (Cortés *et al.* 1984; Robinson 1985; Brown

and Suharsono 1990; Glynn 1990; Greenstein *et al.* 1998). Thus, if the warming of the tropical oceans continues, coral reefs will be severely impacted. For the Florida reef tract, global warming could induce changes in general health and structure, which would reduce both the economic and biological value of these ecosystems.

CHAPTER 2

LEVELS OF DISEASE AND GENERAL CONDITION OF HERMATYPIC SCLERACTINIAN CORALS OF BISCAYNE NATIONAL PARK

INTRODUCTION

Background

The term "disease" refers to "any impairment of an organism's vital functions or systems, including interruption, cessation, proliferation, or other malfunction" (Santavy and Peters 1997). Diseases are classified as either biotic or abiotic. Biotic diseases are those caused by living organisms such as pathogens or parasites, while abiotic diseases result from adverse environmental conditions (Peters 1997; Santavy and Peters 1997). In corals, some potential biotic disease agents include bacteria, protozoans, fungi, and metazoans, while temperature, salinity, solar radiation, sedimentation, oxygen availability and current flow act as abiotic agents. Due to the sessile nature of corals, it is likely that biotic diseases are not spread through physical contact, but rather by some other means (possibly through the water or via other vectors). Abiotic diseases are noninfectious and thus cannot be spread from one coral colony to another. However, the physical conditions that give rise to abiotic diseases can accentuate the effects of a biotic disease by reducing the resistance of the coral organism (Santavy and Peters 1997).

Recent Elevations in Coral Disease Levels

The frequency and distribution of scleractinian coral diseases, along with diseases of other reef-dwelling organisms, are currently proliferating (Peters 1997; Harvell *et al.* 1999). Although the first formal reports of coral disease were made in the 1970's by Antonius (Antonius 1973), the incidence of reportings have undergone considerable

escalation since the late 1980's (Epstein *et al.* 1998; Hayes and Goreau 1998). Many of the so-called diseases that were discovered had not previously been identified and were considered "new" (Epstein *et al.* 1998). The disease outbreaks in conjunction with coral bleaching episodes have added pressure to the already stressed ecosystems, thus contributing to a decline in coral reef vitality. Some of the coral diseases have escalated to epizootic (large increases in the incidence of disease) proportions. Hayes and Goreau (1998) have proposed that the mortality associated with coral reef diseases could easily exceed the damaging effects of sedimentation, pollution, physical degradation, or all other threats combined.

Coral Diseases

Coral disease research is a recently developed discipline as investigations first began less than 30 years ago (Richardson 1998). There are eight presumed diseases that affect corals: Black Band Disease, White Band Disease, Yellow Blotch Disease, Red Band Disease, White (Coral) Plague, White Pox, Rapid Wasting Syndrome, and Dark Spot Disease (Epstein *et al.* 1998; McCarty and Peters 1999). There exists a great deal of confusion surrounding these coral conditions. For example, it has proven very difficult to identify and isolate the causal agents of these diseases. Pathogen(s) have been identified for only Black Band Disease (the cyanobacterium, *Phormidium corallyticum* and its microbial consortium) and White Plague II (bacteria of the genus *Sphingomonas*) (Richardson *et al.* 1998). However, only for White Plague II has the pathogen been demonstrated to be the causal agent (Richardson *et al.* 1998). In order to effectively prove that a specific microorganism is the true cause of a disease, all four of Koch's postulates must be fulfilled (Boyd and Hoerl 1981):

- (1) the microorganism is indefinitely associated with the disease
- (2) the microorganism must be grown in pure culture, isolated from the disease state
- (3) the purely cultured organism must induce disease (with the same set of characteristics) in the host
- (4) the microorganism must be re-isolated from the infected host

The fulfillment of Koch's postulates enables one to distinguish between opportunistic organisms that invade diseased tissue and the true pathogen or parasite (Hayes and Goreau 1998). It has proven very difficult to satisfy all of Koch's postulates for coral diseases because (1) it is difficult to recreate a precise coral reef environment in the laboratory, (2) the natural mechanism of infection is uncertain, and (3) it is difficult to re-isolate the microorganism when the experimental environment (an aquarium) is contaminated by it (Richardson 1998). For those diseases where the infectious agent has not been verified, either the pathogen has not yet been isolated or Koch's postulates have not all been fulfilled (Goreau *et al.* 1998). These coral conditions should be referred to as "potential disease states" until a true etiological agent is determined (Richardson 1998).

The fact that diseases are most likely caused by a variety of contributing factors adds additional complexity to the identification of the causes of these coral conditions (Santavy and Peters 1997). For example, confusion surrounds the relationship between coral bleaching and disease. Several bleaching events have coincided with disease outbreaks (Williams and Bunkley-Williams 1990). These coincidences may suggest two possible scenarios: coral bleaching further reduces the resistance of the coral which makes the coral more susceptible to infection, or diseased corals bleach more readily (Glynn 1993).

Possible Explanations for Elevations in Disease Levels

Corals possess a variety of defense mechanisms including mucous secretion, mesenterial filaments that protect the polyps from invasion and overgrowth, cilia that sweep particles and dissolved substances away from the cell surface, and nematocysts, stinging cells that deter predators and/or invaders. For a host coral to become infected with a disease, the pathogen or parasite must overcome all of these defenses. The emergence of previously unidentified diseases and their rapid proliferation suggest that either coral resistance has been compromised or that the pathogens have become more virulent or adopted different strategies of infection. (Hayes and Goreau 1998)

Disease is the result of the relative contributions of three factors, “a susceptible host, a virulent pathogen, and prevailing environmental conditions” (Peters 1997). If coral resistance is currently being reduced, it could be attributed to environmental degradation in the coral reef ecosystem (Peters 1997; Epstein *et al.* 1998). Epizootics result from an alteration in environmental parameters that either promote increased virulence of the pathogen or encourage the development of a “new” disease (Anderson 1998). Harvell *et al.* (1999) propose that both global warming and anthropogenic activities have encouraged epizootics by reducing the resilience of the host and promoting the spread of the disease. They argue that the recent increases in bleaching and El Niño-Southern Oscillation (ENSO) frequencies are evidence of global climate change and that elevated sea surface temperatures (SSTs) could alter the fundamental physiological processes of the organism, thus reducing its resistance to disease. Elevated water temperature may either promote the proliferation of bacteria and/or suppress coral immunity (Endean 1977; Glynn and D’Croz 1990; Glynn 1993). In addition, human

activity has greatly accelerated the spread of pathogens around the world (Carlton and Geller 1993), and habitat degradation due to anthropogenic factors can lead to epizootics (for references, see Osterhaus *et al.* 1995). Indeed, correlative studies have indicated that coral diseases are found more often in deteriorated environments (Porter and Meier 1992; Kim and Harvell, unpublished data).

Coral Diseases as Indicators

The levels of "new" (previously undescribed) diseases and the reappearance of pre-existing diseases can act as indicators of heightened stress levels and decreased health of an ecosystem (Epstein *et al.* 1998). This idea served as the basis for a large three-year research initiative, funded by the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA), which focused on the documentation of events involving poor health conditions and mortality of marine organisms. One objective of the program, the Health, Ecological, and Economic Dimensions of Global Change Program (HEED), was to monitor both "new" and previously described coral diseases (Epstein *et al.* 1998). This study found that disease levels do in fact act as indicators of ecosystem health and that climatic factors considerably influence the presence of disease.

In this study, current disease levels were assessed for hermatypic corals at reef sites in Biscayne National Park. Only two diseases were observed during the official data collection period for this study: White Band Disease and Yellow Blotch Disease. However, because Black Band Disease is considered in the discussion, it will be described here.

White Band Disease

White Band Disease (WBD) mainly affects members of the family Acroporidae (branching corals), particularly *Acropora palmata* and *Acropora cervicornis* (Santavy and Peters 1997; Goreau *et al.* 1998). WBD was first detected in the Caribbean during the 1970's and has since been observed in Australia, the Gulf of Oman, the Red Sea, and the Pacific Ocean (i.e. the Philippines) (Santavy and Peters 1997). WBD has reached epizootic status in the Caribbean region (Goreau *et al.* 1998). The name refers to a band of white that migrates over the colony, separating the necrotic tissue from the bare coral skeleton (Fig. 11a) (Santavy and Peters 1997; Goreau *et al.* 1998). The white coloration is actually the coral skeleton which is exposed by the peeling or sloughing off of the coral tissue (Fig. 11b) (Santavy and Peters 1997). Algae immediately colonize the exposed areas of the coral skeleton leaving only a band of white at the advancing edge of the disease. The disease generally begins at the base of the colony and, progressing at a rate of 4-5 mm per day, proceeds towards the branch tips. There are two distinct types of WBD that have been identified: WBD I creates a band only a few millimeters wide and WBD II (only observed in the Bahamas, thus far) leaves a band of 5-10 cm wide (Goreau *et al.* 1998; McCarty and Peters 1999).

Although several attempts have been made to determine the etiology of WBD, the causative agent remains uncertain (McCarty and Peters 1999). Peters *et al.* (1983) identified an aggregate of Gram-negative rod-shaped bacteria in the tissues of some colonies with WBD I. These aggregates have also been located in healthy colonies from other locations. However, the number of aggregates per unit area was much greater in diseased than healthy corals, suggesting that a necessary threshold of bacteria is required

a.



b.



Figure 11. (a.) White Band Disease (WBD) on a colony of *Acropora palmata*, Florida Keys. Photo by J. Halas. Source: The Coral Disease Page (McCarty and Peters 1999).
(b.) Close-up view of WBD on a colony of *A. palmata*, U.S. Virgin Islands. Note tissue sloughing at interface between diseased and healthy polyps. Photo by E. C. Peters. Source: The Coral Disease Page (McCarty and Peters 1999).

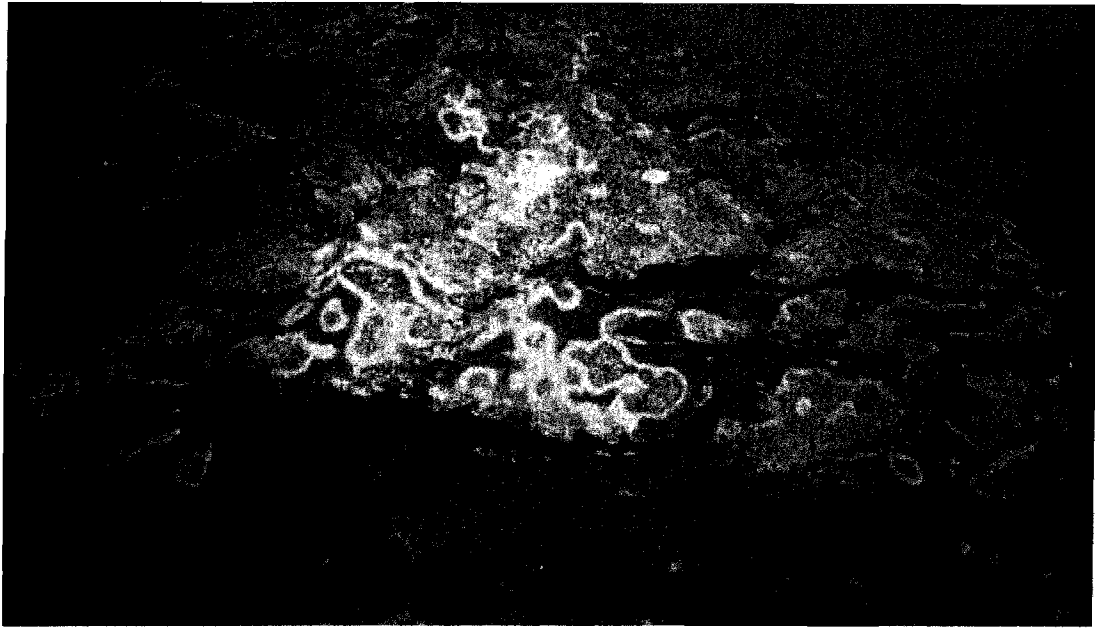
to cause the disease (Peters 1984). The etiology of WBD II also remains undetermined; although, bacteria of the genus *Vibrio* have been observed in the "surface mucous" of the border between the healthy tissue and the white band (McCarty and Peters 1999). Thus, the significance of the association of these bacteria with WBD is unknown.

The documented effects of a WBD epizootic included reductions in the abundance of Acroporids, decreases in the "structural complexity" of the reef, reduced reef accretion, and increases in the abundance of algae and small invertebrates (Gladfelter 1982). The presence of WBD appears to have had devastating impacts on several regions in the Arabian Gulf and throughout the Caribbean, including reefs adjacent to the coasts of the Netherlands Antilles, Panama, and the Florida Keys (Gladfelter 1982; McCarty and Peters 1999). Aronson and Precht (1997) documented the effects of a WBD epizootic on a Caribbean reef. Following the mass mortality of *A. cervicornis* due to infection with WBD, they found that a transition in coral cover occurred from the previously *A. cervicornis*-dominated reef to an *Agaricia spp.*-dominated reef.

Yellow Blotch Disease

Yellow Blotch Disease (YBD) or Yellow Band Disease as it is called in the Arabian Gulf was originally documented by Hayes and Bush (1990) in the Cayman Islands. It has since been observed at many sites throughout the Caribbean including a high incidence in the lower Florida Keys and in the Arabian Gulf (McCarty and Peters 1999). YBD particularly affects species of the genus *Montastrea*, and usually results in death (Santavy and Peters 1997). In more advanced stages, YBD appears as a ring of yellow tissue several centimeters in width (Fig. 12a) (Santavy and Peters 1997; McCarty

a.



b.

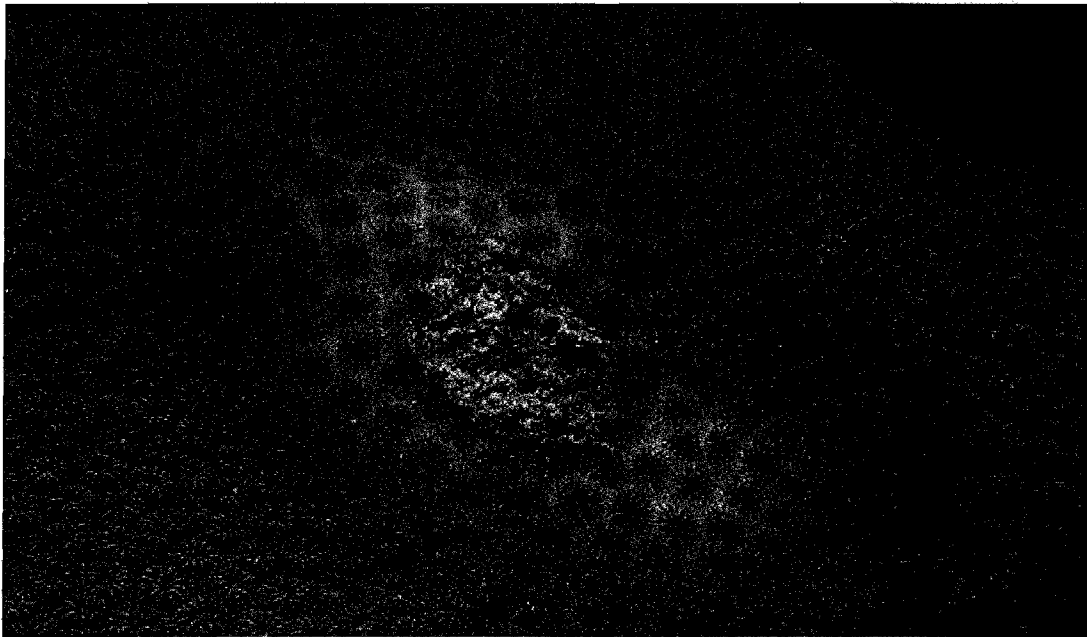


Figure 12. (a.) Yellow Blotch Disease (YBD) on a colony of *Montastraea faveolata*, Panama. Photo by N. Bianchi. Source: The Coral Disease Page (McCarty and Peters 1999). (b.) Close-up of YBD infecting a star coral, Panama. Note the band of yellow tissue surrounding a central patch of sediment and algae. Photo by E. C. Peters. Source: The Coral Disease Page (McCarty and Peters 1999).

and Peters 1999). However, the disease initially appears as a blotch of pale yellow-colored coral tissue (Fig. 12b) (Santavy and Peters 1997). As the center of the blotch dies, sediment and algae cover the skeleton and the disease then appears as a band or ring (Santavy and Peters 1997; McCarty and Peters 1999). The etiological agent of YBD also remains unknown (Santavy and Peters 1997).

Black Band Disease

Black Band Disease (BBD) was the first scleractinian coral disease to be documented (Santavy and Peters 1997). Since its first official report (Antonius 1973), BBD has spread throughout the Caribbean (Peters 1993) and to many areas of the world (for references, see Santavy and Peters 1997). This disease affects all types of coral, but is most prevalent in mound-shaped/boulder corals (Epstein *et al.* 1998). BBD appears as a swiftly moving (several centimeters per day) black band that passes over the coral colony, leaving the white exposed skeleton in its path (Fig. 13a) (Goreau *et al.* 1998). The black band (Fig. 13b) is formed by a "microbial consortium" composed of cyanobacteria, sulfate-reducing bacteria, a sulfur-oxidizing bacterium, ciliates, and heterotrophic bacteria (Rützler and Santavy 1983). It was determined that the anoxic microenvironment at the base of the 1 mm thick band and the hydrogen sulfide produced by the microbial mat were responsible for the tissue necrosis (Richardson *et al.* 1997).

The Purpose of this Study

Coral health surveys provide a relative indication of reef quality which makes it possible to monitor variations in reef health. In addition, levels of disease also give an indication of the health of an ecosystem (Epstein *et al.* 1998). The compilation of baseline data on disease levels is essential in order to serve as a comparison for future

a.



b.

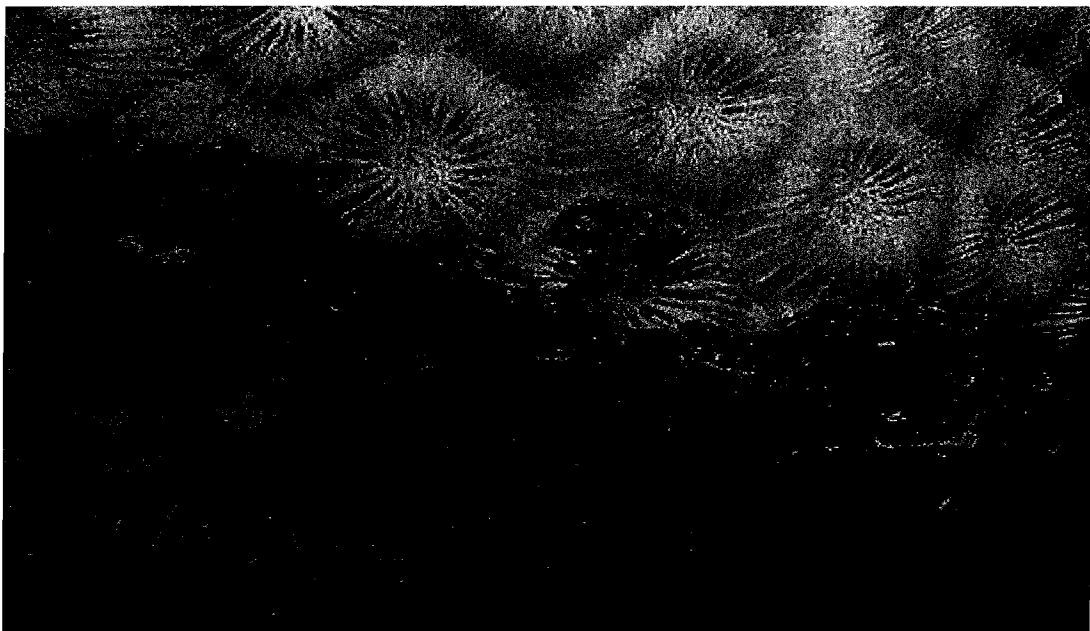


Figure 13. (a.) Black Band Disease (BBD) on a brain coral, Puerto Rico. Photo by E. C. Peters. Source: The Coral Disease Page (McCarty and Peters 1999). **(b.)** Close-up of microbial mat on a colony of *Montastraea cavernosa* infected with BBD. Photo: H. McCarty. Source: The Coral Disease Page (McCarty and Peters 1999).

events in relation to background conditions. In other words, knowledge of background disease levels must be acquired before we can determine whether disease levels are changing. Recently there have been many anecdotal reports that the incidence of coral diseases has increased (Hughes 1994; Sebens 1994; Harvell *et al.* 1999) and reached "epizootic" proportions (Laydoo 1984; Goreau and Hayes 1998; Goreau *et al.* 1998). However, quantitative data on the natural frequency of disease in coral populations are severely lacking. In fact, surveys of disease abundance and distribution have been documented only for BBD. This survey was conducted to establish both the present state of health and baseline disease levels in hermatypic scleractinian corals of Biscayne National Park.

METHODS

Study Sites

A total of five reef sites (Fig. 6) in the southern portion of the Biscayne National Park (BNP) reef tract were surveyed: (1) Pacific Reef (25° 21.961'N, 80° 08.225'W), a bank-barrier reef lying along the outer edge of the reef platform; (2) Picture Reef (25° 21.607'N, 80° 09.996' W), a shallow patch reef located southwest of Pacific Reef approximately equidistant from the eastern and western edges of the reef platform; (3) Richard's Reef (25°21.271'N, 80°11.348'W), a shallow patch reef on the western flank of the platform; (4) Ball Buoy Reef (25° 19.2'N, 80° 11.0'W), the southern-most survey site and one of the most westward lying bank-barrier reefs in this area; and (5) Alina's Reef (25° 23.5'N, 80° 09.9'W), a shallow patch reef located on the western edge of the reef platform. Data on the presence of diseased, bleached, and pale colonies were

collected from all five of the survey sites. However, the specific types of disease and coral health estimates were recorded at only three of the sites (Picture Reef, Pacific Reef, and Richard's Reef).

Coral Disease and Health Data Collection

Surveys were conducted during the months of July and August 1999. Data were gathered by conducting random swims of the survey sites and information was recorded for all hermatypic coral colonies encountered with a greatest dimension of over 25 cm. For each colony, the species was identified and a health category was assigned from a visual examination. The health categories (HCs) refer to estimates of the relative percent of living tissue in the colony. There were four health categories to which surveyed colonies were classified:

HC1 = healthy

HC2 = < 25% partial mortality

HC5 = >25%, but <50% partial mortality

HC7 = >50%, but <75% partial mortality

In addition to the specification of health categories, all observations of coral disease, bleaching, and pale coloration in the surveyed colonies were recorded. Due to the difficulty associated with distinguishing between *Montastrea annularis*, *M. franksi*, and *M. faveolata*, these three species were grouped into the *Montastrea* species complex (*Montastrea spp.*). Specific diseases were identified with the aid of photographic coral disease identification cards produced the National Marine Fisheries Service (NMFS) in collaboration with the University of Puerto Rico Sea Grant (OES 1998).

RESULTS

Disease Levels

A total of 1806 colonies were surveyed within the five study sites.

Approximately 1.3% of these (23 colonies) exhibited some form of biotic disease.

Picture Reef demonstrated the highest frequency of disease with 17 diseased colonies (3.7% of all of the surveyed corals) infected. This survey site also contained the majority (74.0%) of the diseased corals. Approximately 2.3% (3 colonies) of the corals on Pacific Reef were suffering from disease. Lower abundances of disease were observed at Ball Buoy Reef, (0.75%, 3 colonies) and there was a complete absence of disease amongst the surveyed colonies of the remaining two reef sites. An analysis of the disease levels on the patch reefs (Picture Reef, Alina's Reef, and Richard's Reef) versus bank-barrier reefs (Pacific Reef and Ball Buoy Reef) indicated that the higher frequency of disease in the patch reef corals was statistically significant (chi-square test, $p < 0.05$). Diseases were observed in only four species, *Montastrea spp.*, *Porites porites*, *A. cervicornis* and *Colpophyllia natans* (Fig. 14a). Of these species, *Montastrea spp.* exhibited the highest prevalence (82.4%) of disease.

Data on the specific disease form were recorded for a total of 1143 colonies located within three of the six reef sites (Picture Reef, Pacific Reef, and Richard's Reef). Infection was observed only at Picture Reef, and only two diseases were observed, WBD and YBD. Four colonies (0.35% of the surveyed corals) were afflicted with WBD and these were contained within 2 species (Fig. 14b): *Montastrea spp.* which composed 75.0% of the WBD corals (3 individuals) and *A. cervicornis* which encompassed the remaining colony. Thirteen individuals (1.1% of the surveyed corals) were infected with

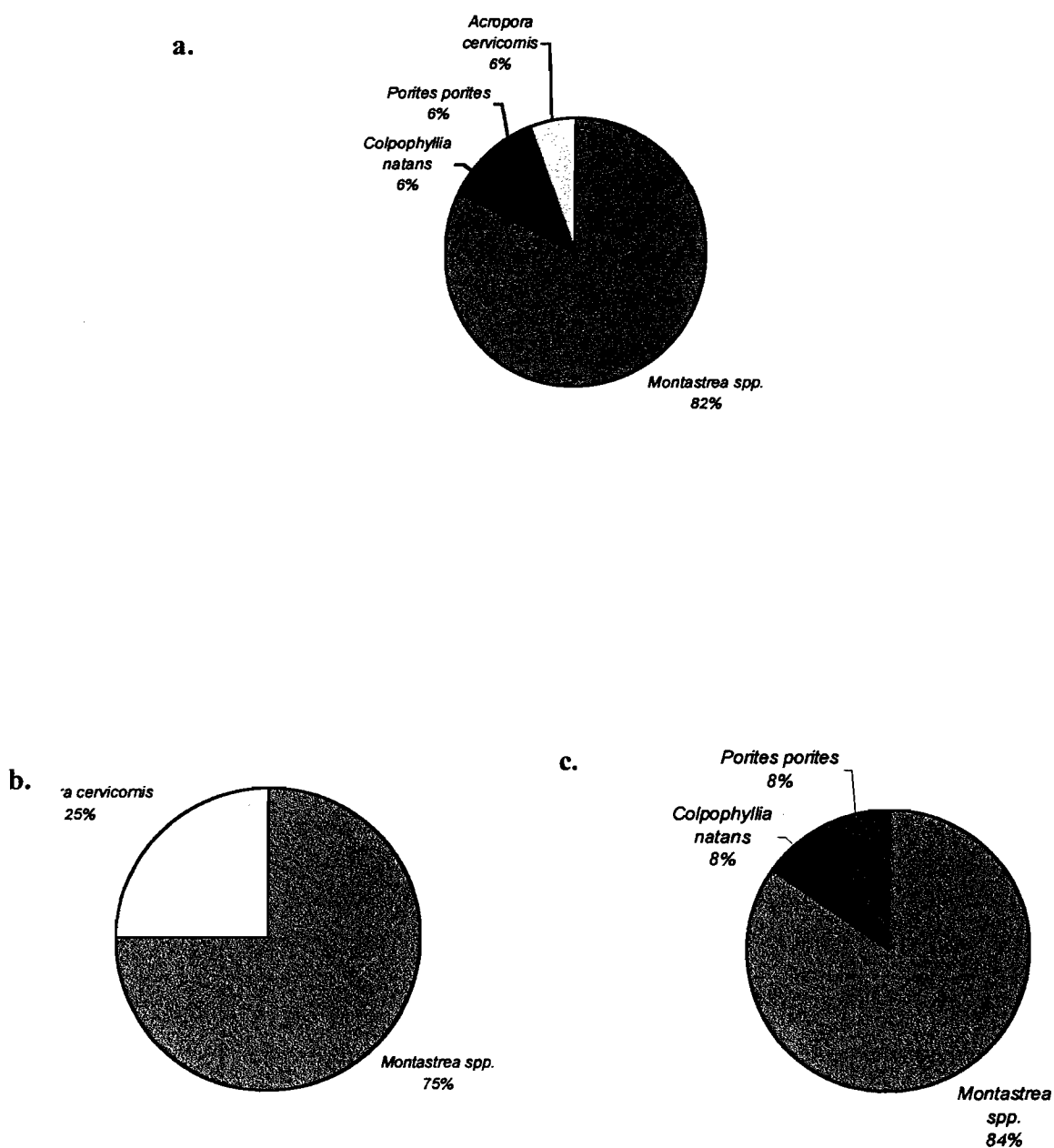


Figure 14. Species composition of diseased corals. The relative percentage of each species is shown for (a.) all diseased colonies (includes data from all survey sites), (b.) WBD colonies, and (c.) YBD colonies.

YBD. YBD constituted over three-quarters of the total number of diseased corals (17 colonies) and 84.6% of the individuals infected with YBD (11 colonies) were of the species *Montastrea spp.* (Fig. 14c). The remaining colonies with YBD were of the species *C. natans* and *P. porites*.

Colony Health

The majority (64.0%) of the 1143 colonies surveyed were healthy, classified under HC1 (Fig. 15), with the percentage of healthy colonies at the individual reef sites ranging from 61.8% to 66.4%. An average of the data from all three survey sites indicates that 26.0% (277 individuals) of the colonies were moderately to severely stressed (HC5 and HC7; 25-75% partial mortality). The survey site with the highest percentage of moderately to severely stressed corals was Picture Reef (28.6% of 461 colonies), followed by Pacific Reef (25.6% of 352 colonies) and Richard's Reef (22.7% of 330 colonies). Four species composed 66.2% of the 157 corals in HC5 (*Siderastrea siderea*, *Montastrea spp.*, *Diploria clivosa*, and *Dichocoenia stokesii*), with *S. siderea* composing approximately one quarter of the corals in this category (Fig. 16). Four species constituted 70.0% of the 120 corals classified as HC7: *Montastrea spp.*, *S. siderea*, *D. clivosa*, and *D. strigosa* (Fig. 16). A total of five species, *Montastrea spp.*, *S. siderea*, *D. clivosa*, *D. strigosa*, and *D. stokesii*, contained approximately 67.9% of the colonies in the HC5 and HC7 categories combined (Fig 16).

Bleached and Pale Colonies

Slightly over 2.0% of the total number (1806) of surveyed colonies were bleached. Alina's Reef exhibited the greatest abundance of bleached corals (8.3% of 133 colonies), followed by Pacific Reef (3.1% of 483 colonies) and Richard's Reef (2.1% of

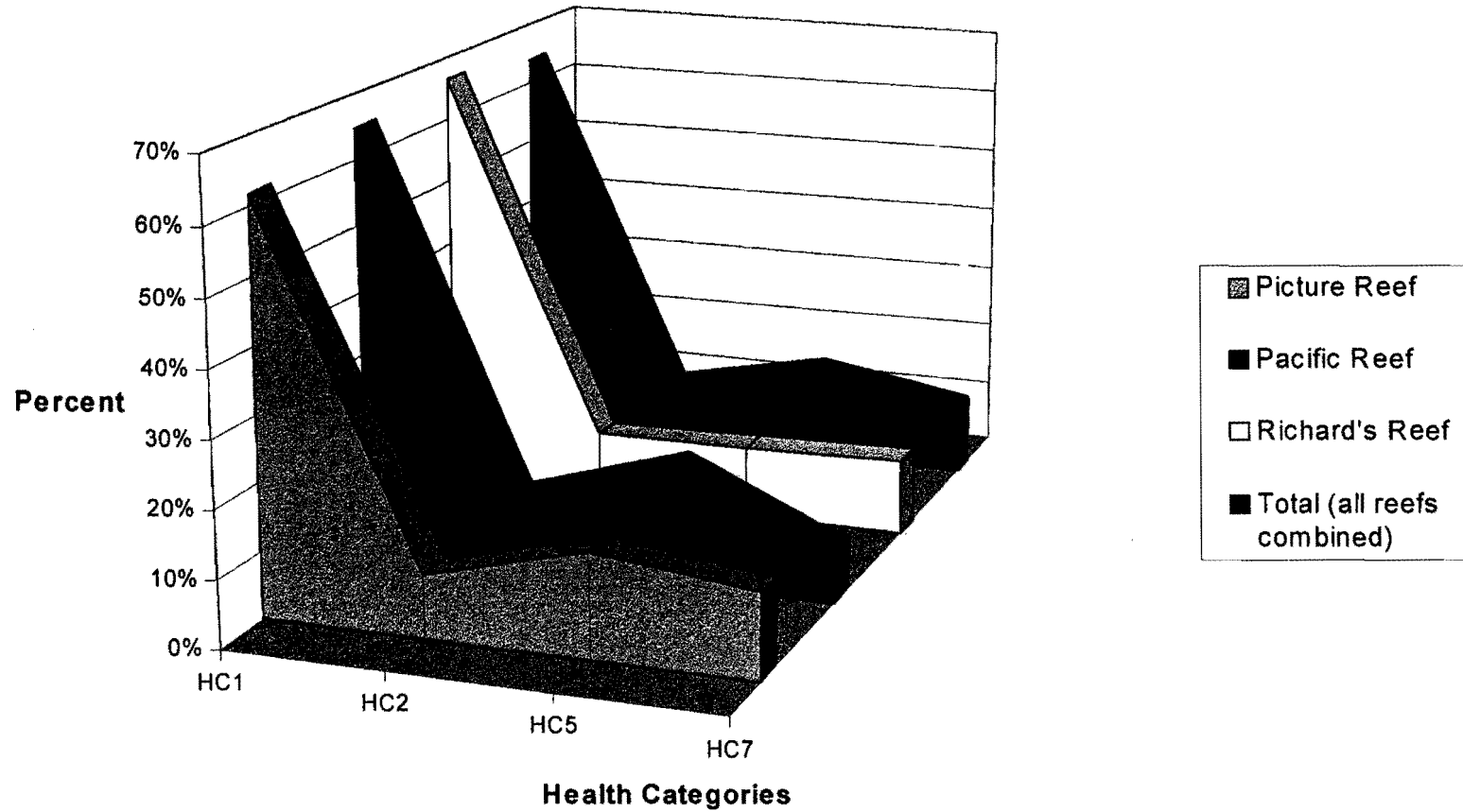


Figure 15. Health of the coral at each reef site. The percentage of coral in each health category (HC) is shown for the three reef sites and for all data points combined.

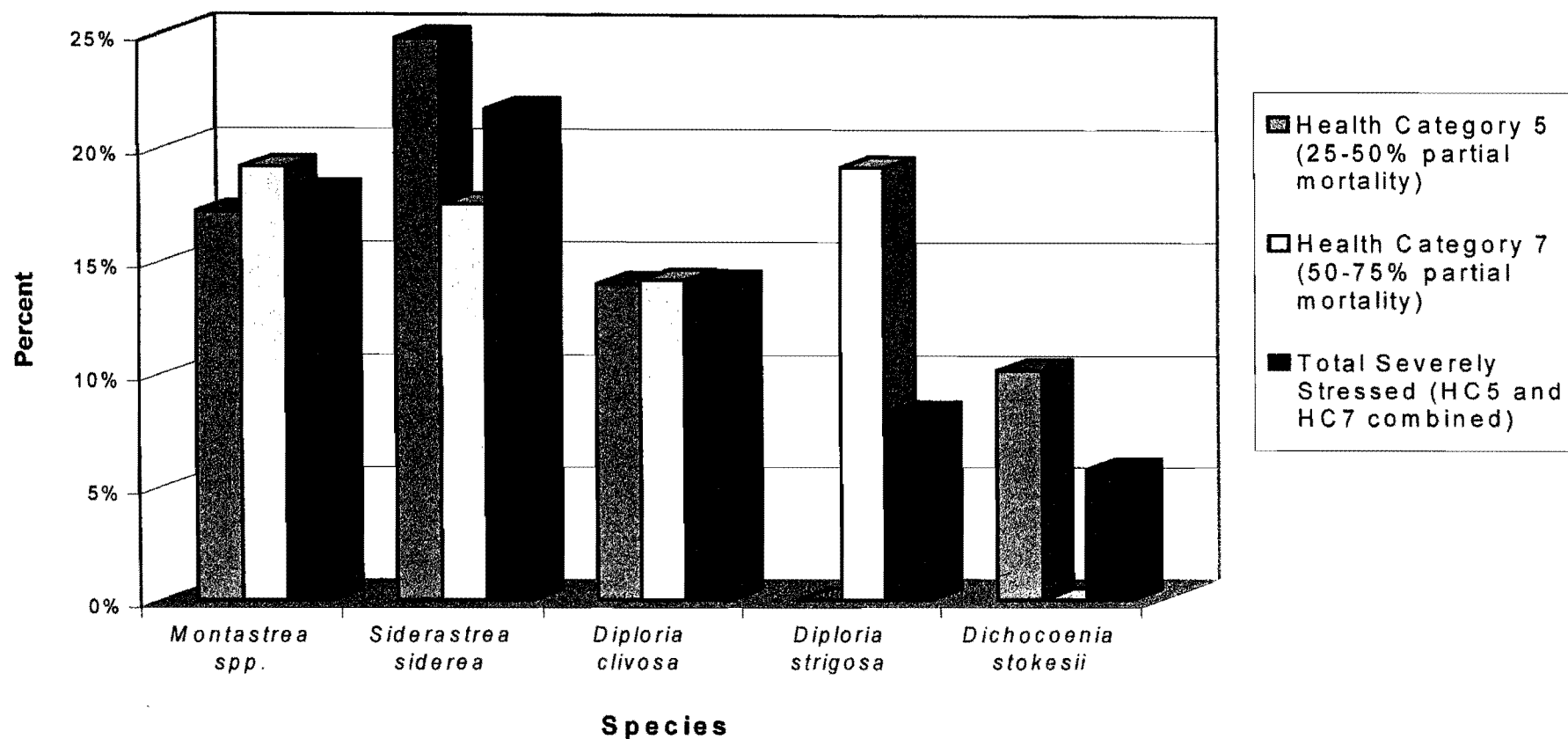


Figure 16. Species composition of moderately to severely stressed corals. Health categories HC5 and HC7 both represent moderate to severe stress (50-75% dead).

330 colonies). Picture Reef (461 colonies) and Ball Buoy Reef (399 colonies) both contained less than 1.0% bleached corals. A total of 13 species exhibited bleaching (Fig. 17). *Agaricia agaricites* was by far the most abundant species of bleached coral (32.4%), while *Favia fragum* and *S. siderea* each composed 10.8% of the total number of bleach corals (Fig. 17). Combined, these 3 species composed approximately 54.1% of the total number of bleached corals.

Data on pale (i.e. partially bleached) colonies was recorded for all survey sites with the exception of Alina's Reef. Of the 1806 colonies surveyed, 3.3% (32 colonies) of these exhibited a "pale" coloration. Approximately 5.8% of the colonies at Pacific Reef were pale, followed by Ball Buoy Reef (3.8%), and Picture Reef (2.8%). The surveyed colonies at Richard's Reef exhibited an absence of pale corals. A total of 12 species displayed some degree of paleness (Fig. 18). *A. agaricites* composed 30.4% of the pale colonies. The four genera, *Diploria*, *Montastrea*, *Porites*, and *Siderastrea*, all contributed significantly to the number of pale colonies, constituting over 60.0% of the pale corals.

DISCUSSION

Disease Levels

The frequency of disease was quite variable among the survey sites, ranging from 0.0% to 3.7%. A survey conducted in the northern Florida Keys (Kuta and Richardson 1996) which used a sample size comparable to the one selected in this survey, found that 0.72% of the surveyed colonies were diseased (infected with BBD). A more extensive study of BBD frequency, conducted on a reef in the U.S. Virgin Islands, found that 0.2%

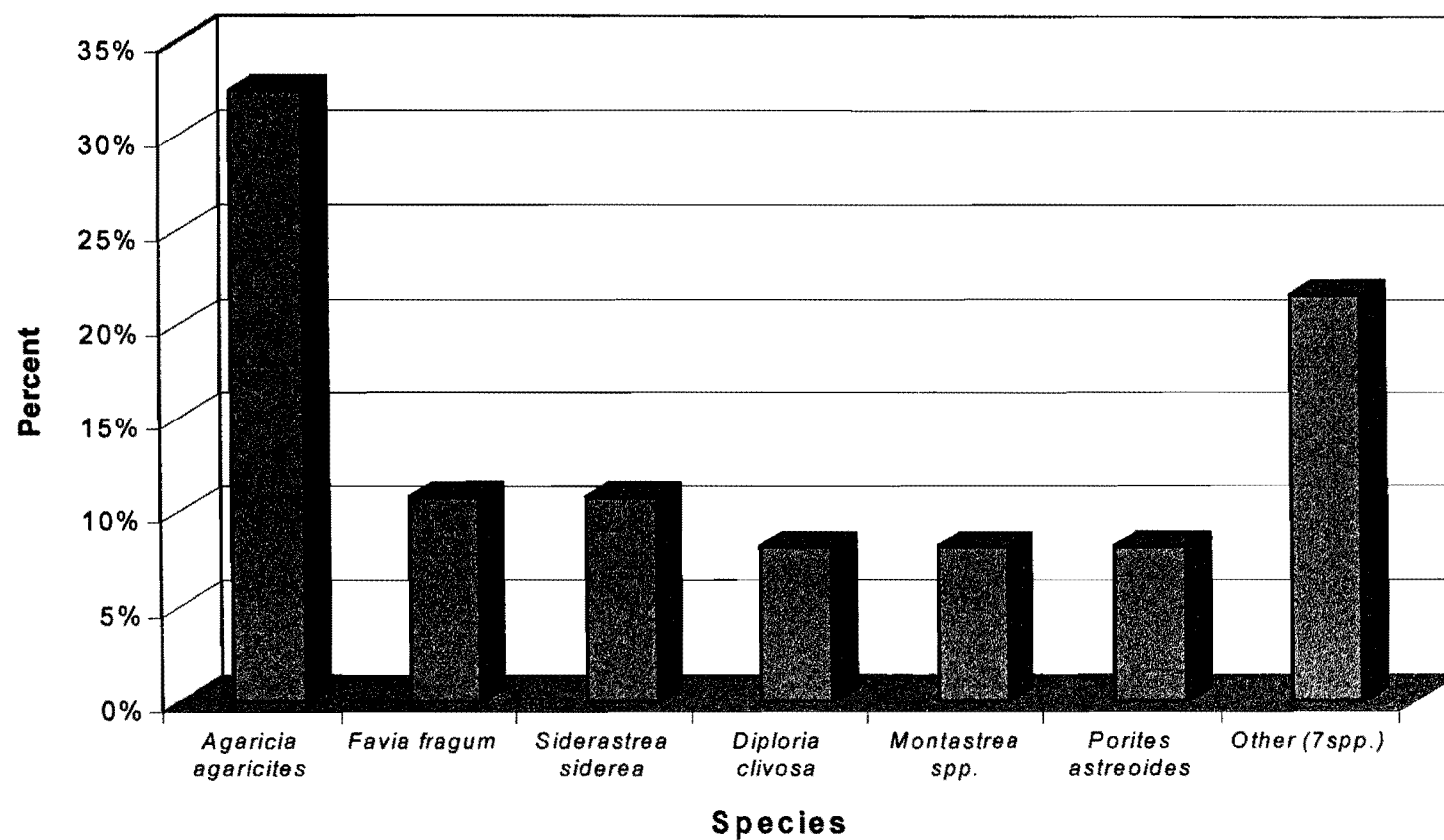


Figure 17. Species composition of bleached corals. The percentage of each species is presented relative to the total number of bleached corals.

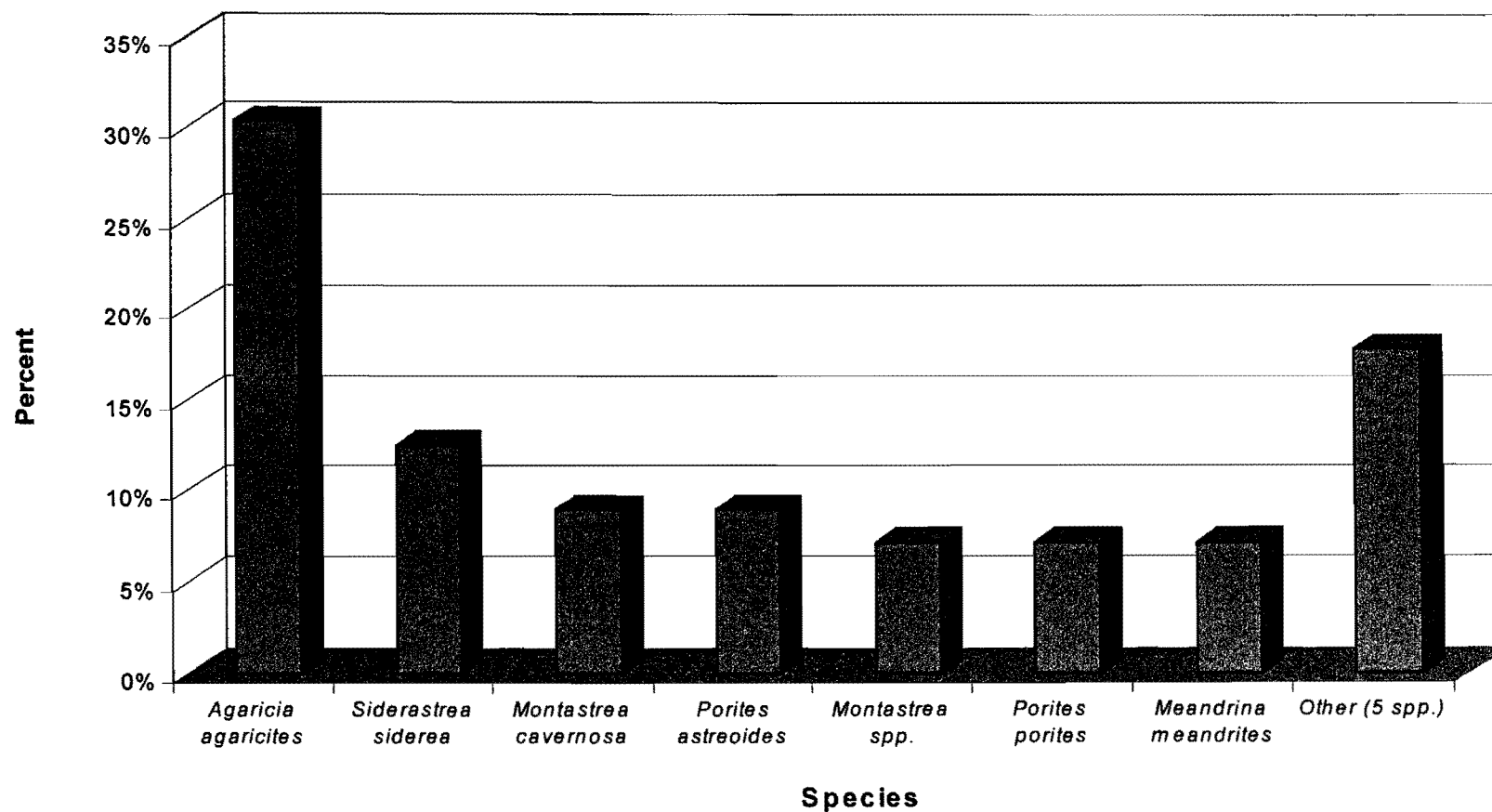


Figure 18. Species composition of pale corals. The percentage of each species is presented relative to the total number of pale corals.

of colonies were infected (Edmunds 1991). The results of these studies suggest that the disease levels at Picture Reef and Pacific Reef are considerably high.

However, these surveys focused only the frequency of BBD, of which no cases were detected in this survey. Therefore, no concrete conclusion can be made regarding the prevalence of WBD and YBD in BNP. Presently, there is a complete absence of quantitative studies of the relative frequencies of WBD and YBD in the Caribbean region. One of the primary objectives of this study was to assess the current levels of these two diseases, as well as others in this area, providing a baseline level of disease against which future studies may compare their findings. Variations in disease levels may be detected and may serve as indicators of prevailing reef vitality.

The location of reef sites in BNP, in relation to the western edge of the reef platform and thus Hawk Channel (Fig. 6), may provide an explanation for higher frequency of disease in coral of the shallow patch reefs on the carbonate platform. Hawk Channel is a shallow sand channel, 4 to 14 m deep, that transports water southward from Biscayne Bay, extending from Miami to Key West (Hudson *et al.* 1994). Because Biscayne Bay is the drainage basin for a portion of the highly populated Florida coast, this water contains elevated levels of contaminants (pollutants and nutrients) and high turbidity. Thus, the water that flows through Hawk Channel probably exhibits these characteristics. Reefs that are confronted with greater exposure to these waters (i.e. the shallow patch reefs on the reef platform such as Richard's Reef, Alina's Reef, and Picture Reef) may be faced with poorer water quality than those reefs influenced by the waters of the Gulf Stream (i.e. the barrier reefs situated at the eastern edge of the platform such as Ball Buoy Reef and Pacific Reef). If contaminated waters are bathing the reefs

influenced by Hawk Channel, then the resistance of these corals may be weakened, making them more susceptible to disease.

The fact that the highest levels of disease were observed in *Montastrea spp.* might suggest that this species is more prone to disease infection than others. Because *Montastrea spp.* is the Caribbean's primary reef-building hermatypic coral species (Meesters and Bak 1993), severe large-scale mortality of this species due to disease could initiate a dramatic loss in coral cover followed by a complete shift in the ecology of the reef (Glynn 1996). A loss of *Montastrea* may permit some opportunistic reef inhabitants such as algae, sponges, and mollusks to invade the unoccupied areas of the reef, inhibiting coral recruitment and possibly altering the species composition and topography of the reef (Glynn 1996).

The finding that *Montastrea spp.* comprised the majority of YBD-infected colonies was not unexpected. YBD is widely recognized as specifically targeting this species and has frequently been observed in areas of the Florida Keys (Goreau *et al.* 1998; McCarty and Peters 1999). The discovery of YBD in *C. natans* and *P. porites* was unanticipated since no published documentation was found associating either of these species with the disease. The unexpected result may be attributed to misidentification of the disease or a lack of published accounts of YBD in these species.

The establishment of *Montastrea spp.* as the species with the highest abundance of WBD was not unexpected. Although WBD primarily afflicts Acroporid corals (*A. cervicornis* composed 25.0% of the colonies infected with WBD), it has also been observed in *Montastrea spp.* (Antonius 1981). Many observations of the association

between WBD and this species have been documented, including several in the Florida Keys (Antonius 1981; Ritchie and Smith 1997,1998; McCarty and Peters 1999).

One surprising result of this survey was the apparent absence of BBD at the reef sites. This disease is fairly common throughout the Caribbean including the Florida Keys (Antonius 1973; Garrett and Ducklow 1975; Peters 1993) and is particularly prevalent, reaching epizootic proportions, during the summer months (Edmunds 1991; Kuta and Richardson 1996). Kuta and Richardson (1996) found that colonies in the Florida Keys infected with BBD exhibited a clumped distribution. This finding may offer a possible explanation for why BBD was not observed during this survey. If the diseased colonies in BNP were also present in clumps, it is possible that the random swims that were conducted simply failed to sample any of the disease clusters.

Colony Health

Although the majority of corals were classified as healthy, a significant amount of corals displayed some form of stress. Over one quarter of the corals surveyed for health were moderately to severely stressed (H5 and H7), possibly suggesting that adverse environmental conditions due to natural and/or anthropogenic stressors such as temperature, salinity, irradiance extremes, pathogens, pollution, or sedimentation may have been present. However, due to the lack of comparable data from other studies, no conclusion can be drawn concerning the present state of health of these reefs in BNP. The collection of additional data in the future will allow the stability of the relative reef health to be determined, thus providing an indicator of the variation in environmental conditions.

Three species of coral, *Montastrea spp.*, *S. siderea*, and *D. clivosa*, were found to exhibit moderate to severe levels of stress, possibly because they are less tolerant of adverse conditions than other coral species. The fact that these species have previously been associated with moderate to extreme bleaching (Wilkinson 1998a), an additional stress indicator, supports this idea. If the environmental conditions on these reefs were to worsen, mortality of entire colonies may result. Mass mortality of any dominant coral species could drastically change the reef structure, as was previously described.

Bleaching and Paleness

Both bleaching and "pale" coloration in corals are considered a generalized stress response to a variety of adverse environmental conditions. The generally low abundance of bleached corals in this survey might suggest that low amounts of stress are present among the reefs. An additional explanation might be that ambient temperatures were not warm enough to initiate bleaching. The elevated bleaching frequencies at Alina's Reef may result from an increased amount of local stresses, possibly turbidity or pollutants, at this location.

The species composition of bleached corals found in this study agree with results in the literature. Our finding of *A. agaricites* as the most commonly bleached and pale species is similar to the results from other surveys in the Caribbean (e.g. Williams and Bunkley-Williams 1988; Savina 1991; Pecheaux 1995; Wilkinson 1998a). A general consensus exists among coral researchers that the corals of the genus *Agaricia* are frequently the first to experience bleaching. Although there are exceptions, coral bleaching research has generally indicated that branching and platy species of coral (*A. agaricites* is considered a platy species) tend to bleach earlier and more often than other

species (Glynn 1990; Williams and Bunkley-Williams 1990). Corals of the genus *Montastrea* have also been observed to bleach frequently in the Caribbean and elsewhere (Pechaux 1995; McGrath and Smith 1998; Wilkinson 1998a; Wilkinson 1998b), which corroborates our findings. The higher frequency of bleaching in these species may also be explained by a decreased resilience to adverse environmental conditions. Intraspecific variations in bleaching also exist where colonies of the same species have differential tolerances and bleach at different rates (Glynn 1996). This may be the result of variations in host susceptibility (Gates *et al.* 1992), variations in the susceptibilities of different zooxanthellae strains (Rowan and Knowlton 1995), or small-scale differences in the immediate environment (Glynn 1996).

While this study provides a baseline level on the prevalence of disease on the reefs of BNP, observations are limited to the months of July and August 1999. A longer study would allow for the detection of seasonal variations in coral health and disease levels. To effectively determine typical background health and disease data and assure representative sampling, a larger number of coral colonies must be surveyed. With the low numbers of diseased corals observed in this survey, it becomes necessary to examine a greater number of colonies in order to detect some of the less frequent coral species and diseases. However, it is difficult to increase the frequency of the surveys considering the intense demands on time and effort that this type of investigation requires.

As this survey of reef health and disease will continue on in the future, several recommendations might be made concerning the collection of additional data. First, as suggested by Santavy and Peters (1997), some ancillary information should be documented including water temperature, depth of survey, and photographs of the

diseased colonies. Also, it would be informative to include the degree of bleaching, whether minor (partial bleaching) or severe (total bleaching), in the data collection.

Furthermore, it would be helpful to select additional survey sites in order to establish a latitudinal gradient from North to South throughout BNP. This would better allow for the detection of the affects of different water masses (i.e. Biscayne Bay water versus Gulf Stream water) on the reef sites.

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