

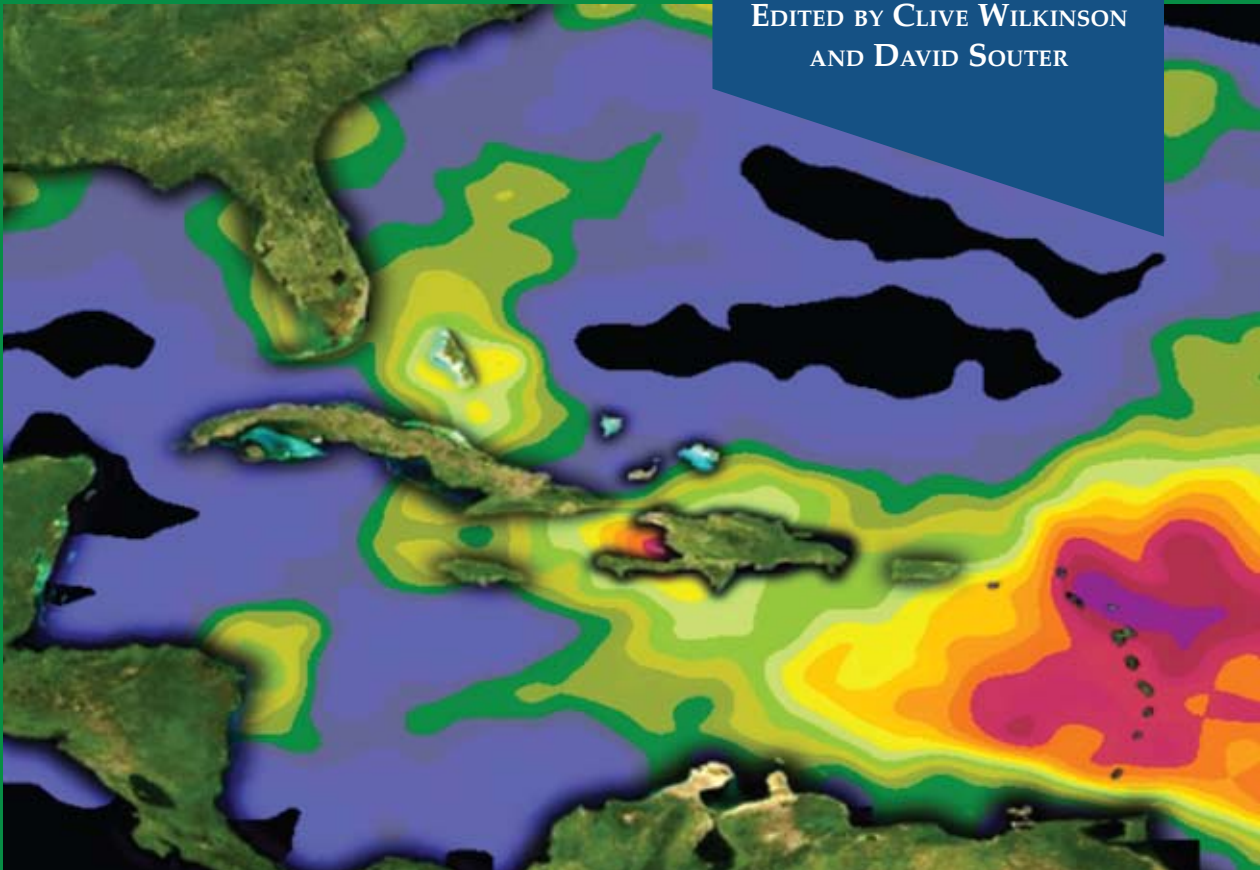
GCRMN
GLOBAL CORAL REEF
MONITORING NETWORK

ICRI
INTERNATIONAL
CORAL REEF INITIATIVE



STATUS OF CARIBBEAN CORAL REEFS AFTER BLEACHING AND HURRICANES IN 2005

EDITED BY CLIVE WILKINSON
AND DAVID SOUTER



IUCN
The World Conservation Union



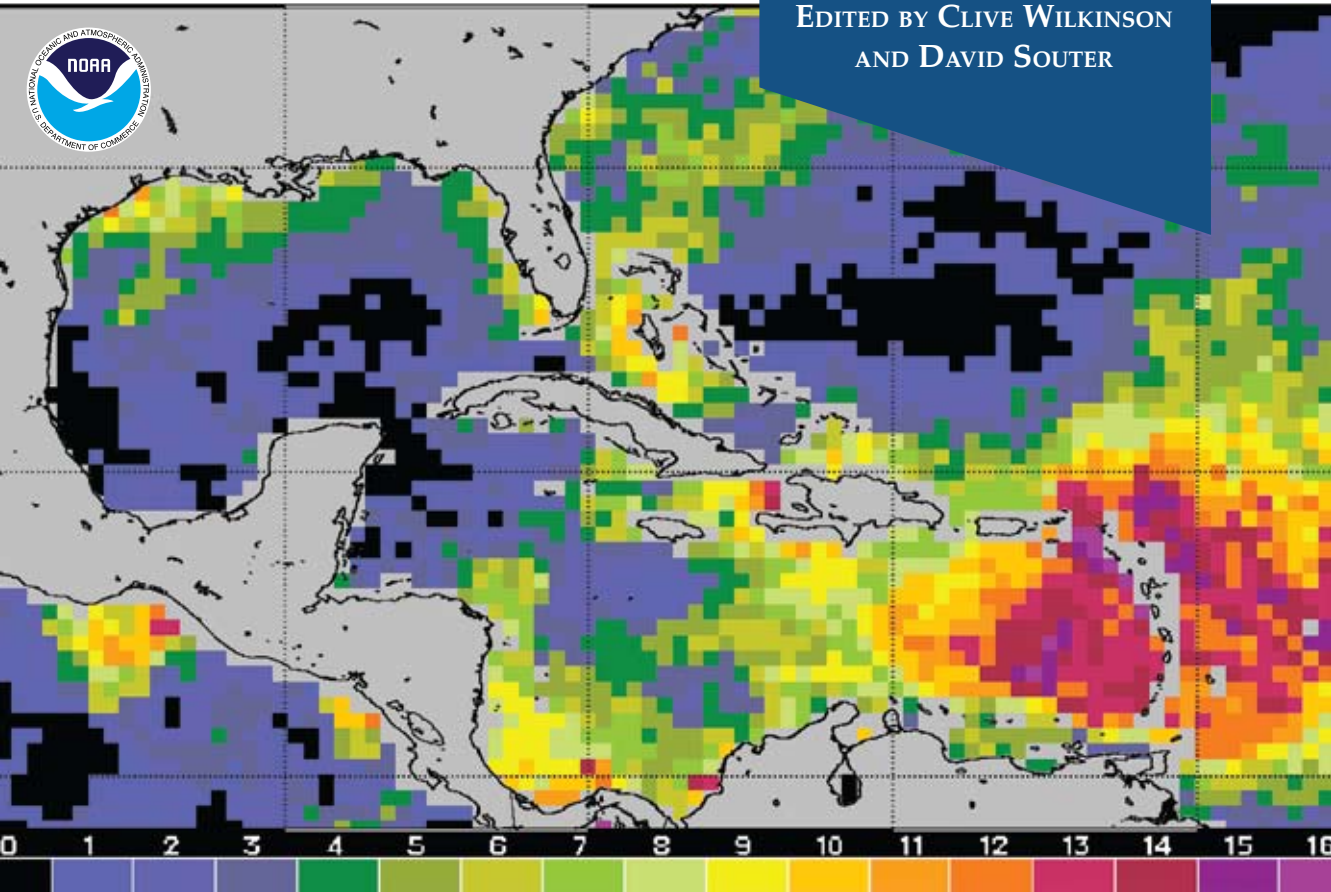
ICRAN
International Coral Reef Action Network



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Dedication: This book is dedicated to the many people who have worked on coral reefs to understand them and ensure that they exist for future generations. One of these deserves special mention; Len Muscatine retired from UCLA to his vineyard but did not have enough time to enjoy the fruit of his vines. We miss him. The book is also recognises the International Coral Reef Initiative and partners, and particularly those people in the USA, operating through the US Coral Reef Task Force, the US Department of State and the US National Oceanic and Atmospheric Administration, who continue to strive for greater recognition of the problems facing coral reefs and the need for urgent conservation efforts.

Note: The conclusions and recommendations of this book are solely the opinions of the authors and contributors and do not constitute a statement of policy, decision, or position on behalf of the participating organizations.

Front Cover: A stylized map of the maximum Degree Heating Week values observed across the Caribbean during 2005, indicating the highest level of accumulated thermal stress at each location (image from US National Oceanic and Atmospheric Administration Coral Reef Watch).

Inside Title Page: This image shows the 2005 maximum Degree Heating Week data used to create the image on the front cover, showing the maximum level of accumulated thermal stress at each location (explained on pages 38 and 39; image from US National Oceanic and Atmospheric Administration Coral Reef Watch).

Back Cover: A NOAA/Biogeography Branch diver with a 1 metre by 1 metre quadrat examining a bleached *Montastraea* colony at St Croix, US Virgin Islands (photo from NOAA Center for Coastal Monitoring and Assessment Biogeography Branch).

Maps were provided by UNEP-WCMC through ReefBase, The WorldFish Center; we thank them.

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GCRMN Management Group

IOC-UNESCO –Intergovernmental Oceanographic Commission of UNESCO
UNEP – United Nations Environment Programme
IUCN – The World Conservation Union (Chair)
The World Bank, Environment Department
CBD – Convention on Biological Diversity
AIMS – Australian Institute of Marine Science
GBRMPA – Great Barrier Reef Marine Park Authority
RRRC – Reef and Rainforest Research Centre (host)
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GCRMN Operational Partners

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FOREWORD

Here in 2008, we are in the midst of the International Year of the Reef as designated by the International Coral Reef Initiative (ICRI). This year-long campaign of events and initiatives is aimed at promoting conservation action and building long-term partnerships for sustaining coral reef systems.

1992 was also a critical year for the world's environment. World leaders met in Rio de Janeiro at the United Nations Conference on Environment and Development (UNCED) to sign the Convention on Biological Diversity and also pledge major resources for environmental action. The Rio Conference also led to negotiations that transformed the Global Environment Facility (GEF) from a pilot program to a permanent financial mechanism in support of the global environment. Estimates were also made in 1992 that the world had already lost 10% of the coral reefs and that a further 60% were under threat of destruction if urgent actions to implement sustainable use and conservation of the reefs were not implemented. In the 16 years since these estimates were made at the 7th International Coral Reef Symposium in Guam, alarming increases in degradation of coral reefs have been reported.

The events of 1992 catalyzed the formation of the ICRI as well as the Global Coral Reef Monitoring Network (GCRMN), which has supported production of this book. Chapter 17 of Agenda 21 that was agreed at UNCED highlighted that coral reefs warranted special attention. This was re-affirmed at the World Summit on Sustainable Development in 2002 in Johannesburg, which also provided an incentive for countries to work with the GEF to conserve valuable marine resources. The Johannesburg Summit urged that small countries be given additional assistance to: adopt integrated approaches for watershed, coastal and marine management; recognise traditional knowledge and management methods; increase the involvement of communities and the private sector in managing coral reefs; improve their capacity to monitor, conserve and sustainably manage coral reefs and associated ecosystems; and create representative networks of marine protected areas for the conservation and management of coral reefs, mangrove forests and seagrass areas.

The GEF attaches critical importance to the health of coral reefs as nearly 500 million people across the world depend on them for food, coastal protection, livelihoods, and tourism income. This includes about 30 million particularly poor people who depend almost entirely on coral reefs for food and protection. The agenda for coral reef conservation in 1992 focused on managing the impacts of coastal communities through a new focus on sustainable development of these resources. Management efforts were aimed at reducing the impacts from the land of excess sediment flows from poor land use, nutrient pollution from human, agricultural and industrial wastes, as well as over-exploitation and damaging fishing practices, and damaging modification of shorelines.

But that agenda changed after 1998 during the large El Niño and La Niña shift in the global climate that resulted in massive coral bleaching. Approximately 16% of the world's coral reefs died in 1998 with especially severe damage in the Indian Ocean and Western Pacific. All of us involved in conservation had to focus on the emerging and increasing threat that global climate change brings to coral reefs with stressful temperatures, rising sea levels, and threatening the ability of corals to survive in potentially more acidic waters.

Another significant event related to coral reefs occurred in 2005. This book, *Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005*, documents the devastating effects on coral reefs from the hottest year on record with its very high sea surface temperatures and record hurricane activity throughout the Caribbean and Atlantic basins. The development of this report has brought together 71 coral reef scientists and managers, predominantly from developing countries, to catalogue the impacts of the warming and storms during 2005 and subsequently in 2006.

This detailed information is valuable for environmental managers and supporting agencies to underscore urgent actions needed to assist reefs in recovery by focusing on natural resistance and resilience as well as removing threats posed by human activities that slow or even prevent recovery from these damaging events. More importantly, these findings are particularly critical for the peoples of the Caribbean who are highly dependent on these coral reef resources for providing natural defences in terms of coastal protection against storms and a buffer against sea level rise. Healthy coral reefs also continue to provide food and family income, including tropical tourism.

Last year, the GEF launched a series of new programmatic approaches to support many of the Small Island Developing States (SIDS). I had the privilege with Heads of State and top government officials from Pacific Island Countries to announce a new type of GEF programmatic approach toward sustainable development of islands. Known as the Pacific Alliance for Sustainability, the program supports a number of linked GEF operations addressing biological diversity, climate change mitigation and adaptation, and integrated approaches toward land and water resources management. This new approach comes on the heels of successful GEF projects for the Caribbean such as the Mesoamerican Barrier Reef System Project and the landmark GEF Coral Reef Targeted Research and Capacity Building project that is working through a Center of Excellence in Mexico and others globally in developing countries to find solutions to improve coral reef management to sustain these valuable ecosystems.

Throughout the years I have developed a deep appreciation of the traditions and the reliance of island communities on the coral reefs and lagoons. For those who also have interest in these critically important systems, I recommend this report on the *Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005* and ask you to join the global effort to conserve our planet's coral reef systems.



Monique Barbut
Chair and Chief Executive Officer
Global Environment Facility



EXECUTIVE SUMMARY

CLIVE WILKINSON AND DAVID SOUTER

2005 – a hot year

- 2005 was the hottest year in the Northern Hemisphere on average since the advent of reliable records in 1880.
- That year exceeded the previous 9 record years, which have all been within the last 15 years.
- 2005 also exceeded 1998 which previously held the record as the hottest year; there were massive coral losses throughout the world in 1998.
- Large areas of particularly warm surface waters developed in the Caribbean and Tropical Atlantic during 2005. These were clearly visible in satellite images as HotSpots.
- The first HotSpot signs appeared in May, 2005 and rapidly expanded to cover the northern Caribbean, Gulf of Mexico and the mid-Atlantic by August.
- The HotSpots continued to expand and intensify until October, after which winter conditions cooled the waters to near normal in November and December.
- The excessive warm water resulted in large-scale temperature stress to Caribbean corals.

2005 – a hurricane year

- The 2005 hurricane year broke all records with 26 named storms, including 13 hurricanes.
- In July, the unusually strong Hurricane Dennis struck Grenada, Cuba and Florida.
- Hurricane Emily was even stronger, setting a record as the strongest hurricane to strike the Caribbean before August.
- Hurricane Katrina in August was the most devastating storm to hit the USA. It caused massive damage around New Orleans.

- Hurricane Rita, a Category 5 storm, passed through the Gulf of Mexico to strike Texas and Louisiana in September.
- Hurricane Wilma in October was the strongest Atlantic hurricane on record and caused massive damage in Mexico, especially around Cozumel in Mexico.
- The hurricane season ended in December when tropical storm Zeta formed and petered out in January.
- Many of these hurricanes caused considerable damage to the reefs via wave action and runoff of muddy, polluted freshwater.
- The effects were not all bad. Some hurricanes reduced thermal stress by mixing deeper cooler waters into surface waters.
- Although there were many hurricanes, none passed through the Lesser Antilles to cool the waters, where the largest HotSpot persisted.

2005 – a massive coral bleaching event

- The warm water temperatures caused large-scale coral bleaching as a stress response to the excessive temperatures.
- Bleached corals were effectively starving and susceptible to other stresses including diseases; many died as a result.
- The first coral bleaching was reported from Brazil in the Southern Hemisphere; but it was minor.
- The first bleaching reports in the Caribbean were in June from Colombia in the south and Puerto Rico in the north.
- By July, bleaching reports came in from Belize, Mexico and the U.S. Virgin Islands affecting between 25% and 45% of coral colonies.
- By August, the bleaching extended to Florida, Puerto Rico, the Cayman Islands, the northern Dutch Antilles (St. Maarten, Saba, St. Eustatius), the French West Indies (Guadeloupe, Martinique, St. Barthelemy), Barbados and the north coasts of Jamaica and Cuba.
- Bleaching in these countries was generally severe affecting 50% to 95% of coral colonies.
- In some countries (e.g. Cayman Islands) it was the worst bleaching ever seen.
- By September, bleaching affected the south coast of Jamaica and the Dominican Republic, with 68% of corals affected;
- By October, Trinidad and Tobago was reporting 85% bleaching, and the development of a second HotSpot was causing the most severe bleaching for the last 25 years; some places reported 100%, although it was highly variable between sites;
- By November, minor bleaching also affected Venezuela, Guatemala and the Dutch islands of Bonaire and Curacao, affecting 14% to 25% of corals.
- In many countries (Cuba, Jamaica, Colombia, Florida, USA) there was great variation in bleaching between sites. In Florida, areas exposed to regular large temperature fluctuations, and nutrient and sediment loads were less affected. In the French West Indies, the variation was attributed to different species composition between sites.

- The corals vulnerable to bleaching were similar across the Caribbean, particularly: *Acropora palmata* and *A. cervicornis*, *Agaricia*, *Montastraea*, *Colpophyllia*, *Diploria*, *Siderastrea*, *Porites*, the hydrozoan *Palythoa* and the hydrocoral *Millepora*, which has nearly disappeared from the French West Indies.
- Bleaching persisted to mid-2006 in Guadeloupe, Martinique, Barbados and Trinidad and Tobago, and, in 2007 in St. Barthelemy. Reefs in these countries showed few signs of recovery, with between 14% and 33% of colonies still bleached.

2005 – extensive coral mortality and disease

- The greatest damage occurred in the islands of the Lesser and Greater Antilles where corals were bathed in abnormally warm waters for 4 to 6 months.
- The greatest coral mortality occurred in the U.S. Virgin Islands, which suffered an average decline of 51.5% due to bleaching and subsequent disease; the worst seen in more than 40 years of observations.
- Barbados experienced the most severe bleaching event ever with 17% to 20% coral mortality.
- Losses in the French West Indies ranged between 11% and 30%.
- In the northern Dutch Antilles, there was 18% mortality in St. Eustatius, but minimal mortality in Bonaire and Curacao in the south.
- Trinidad and Tobago suffered considerable mortality, with 73% of all *Colpophyllia* and *Diploria* colonies dying.
- Although there was severe bleaching in the Greater Antilles, minimal mortality occurred in Bahamas, Bermuda, Cayman Islands, Cuba, Jamaica and Turks and Caicos; some sites in the Dominican Republic, however, suffered up to 38% mortality.
- Bleaching mortality was minimal on the Mesoamerican Reef system, largely because many storms cooled sea temperatures; however, Hurricanes Emily and Wilma damaged some reefs, decreasing coral cover from 24% to 10%, especially around Cozumel.
- Coral mortality in Colombia and Venezuela was negligible.
- Increased prevalence of disease following bleaching was reported from many islands of the Lesser Antilles, particularly French West Indies; infection rates increased from 33% to 39% on Guadeloupe and 18% to 23% on St. Barthelemy; 49% of corals were infected on Martinique.
- In Trinidad and Tobago, there was clear evidence of an increase in the prevalence of disease.
- In the U.S. Virgin Islands, secondary disease infections killed bleached colonies of *Montastraea*, *Colpophyllia*, *Diploria* and *Porites*.

2005 – lessons for management and future options

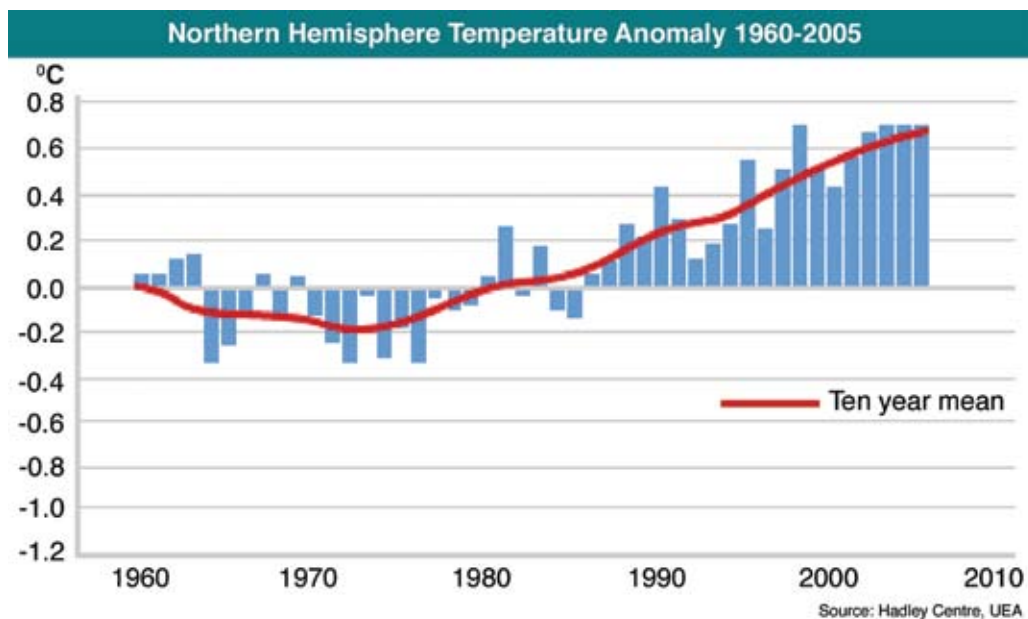
- Unfortunately direct management action is unlikely to prevent coral bleaching and mortality from climate change on most of the world's reefs.
- However, effective management can reduce the damage from direct human pressures and encourage the natural adaptation mechanisms to build up reef resilience;

- Such actions will promote more rapid recovery in the future, especially if bleaching will become a regular event.
- Unfortunately, current predictions are for more frequent and intense warming in the Caribbean with the high probability of increased bleaching and coral mortality.
- Severe coral bleaching is predicted to become a more regular event by 2030, and an annual event by 2100, if the current rate of greenhouse emissions is not reversed.

INTRODUCTION

The most extreme coral bleaching and mortality event to hit the Wider Caribbean (including Atlantic) coral reefs occurred in 2005. This was during the warmest year ever recorded, eclipsing the 9 warmest years that had occurred since 1995. The previous warmest year was 1998, which resulted in massive coral bleaching throughout many parts of the world and effectively destroyed 16% of the world’s coral reefs, especially in the Indian Ocean and Western Pacific.

Unlike the events of 1998, this climate-related bleaching event did not occur in an information vacuum; this time there were many scientific tools available and alerts issued to those working and managing coral reefs in the Caribbean to assess the damage and possibly prepare management responses to reduce the damage. This book explains coral bleaching and follows the sequence of the events leading up to it, and documents much of the damage that occurred to the coral reefs and consequently to the people dependent on coral reefs for their livelihoods in the Wider Caribbean.



This graph from the Hadley Climate Center in the UK shows that surface temperatures in the Northern Hemisphere have been much higher in the last two decades and appear to be increasing from the baseline of temperatures in 1960. The red line is a 10 year running average.

It May 2005, analysis of satellite images by the National Oceanic and Atmospheric Administration (NOAA) of USA showed that the waters of the Southern Caribbean were warming faster than normal and people in the region were asked to look out for coral bleaching. The warming was evident as a 'HotSpot' of warmer water which was likely to stress corals in the Northern Caribbean (see p. 38).

As the surface waters continued to heat up, it became obvious that this was going to be a particularly stressful year for the coral reefs of the Caribbean. NOAA issued a regular series of information bulletins, warnings and alerts on the warming waters and developing hurricanes, thereby stimulating coral reef managers and scientists to examine their coral reefs for signs of bleaching. Throughout August, September and October it became clear in reports from the Wider Caribbean that 2005 was probably the most severe coral bleaching and mortality event ever recorded. The HotSpot warming reached its peak in October and then dissipated as winter approached and solar heating shifted to the southern hemisphere. However, monitoring of the corals continued into 2006 to assess either recovery from bleaching, or incidences of coral disease or mortality. There were also preliminary assessments of the social and economic costs of this HotSpot phenomenon.

The 2005 bleaching event has followed a long, slow decline in the status of Caribbean coral reefs over thousands of years; especially during the last 50 years. Many Caribbean reefs have lost up to 80% of their coral cover during this time. The causes included climate related factors prior to 2005, but most of the coral losses were due to direct human impacts such as over-fishing, excess sediment input, increases in nutrients from agriculture and domestic sewage, and direct damage to reefs during development. These impacts are all symptomatic of increasing human populations and their use of the reefs, such that many of these occur simultaneously. The damage symptoms are often seen as particularly low fish populations, outbreaks of coral diseases, or corals struggling to grow in poor quality, dirty waters or smothered by algae. Thus many of the reefs of the Wider Caribbean were already stressed and in decline when the major climate change events of 2005 struck.

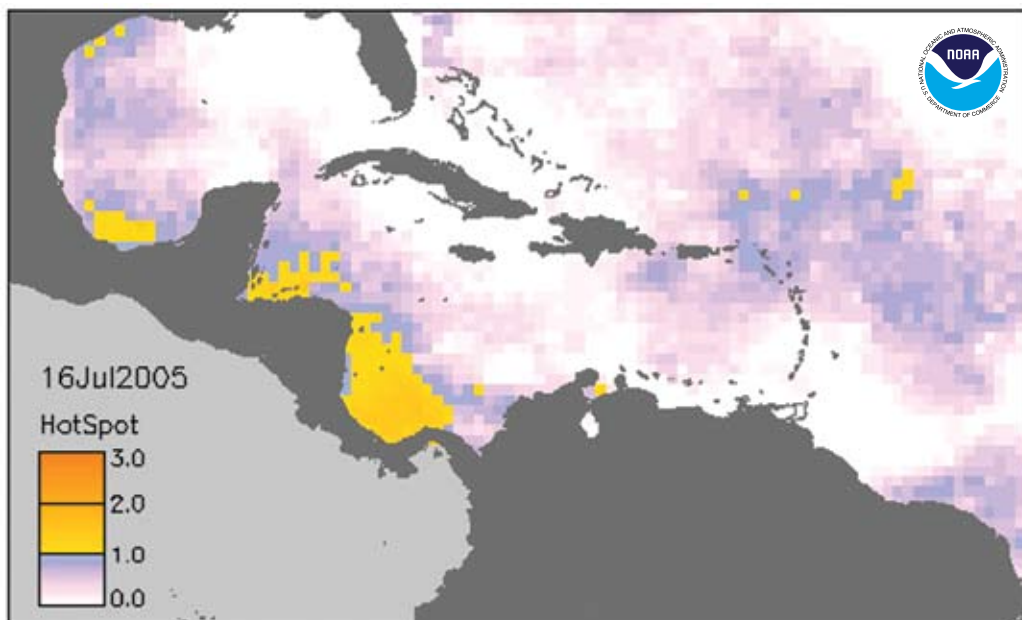
The islands and mainland countries of the Caribbean are highly dependent on coral reef resources, thus there is an urgent need for appropriate management responses as sea temperatures are predicted to increase further in future. The World Resources Institute Reefs@Risk analysis estimated that Caribbean coral reefs in 2000 provided between US\$3,100 million to \$4,600 million each year from fisheries, dive tourism, and shoreline protection services; however 64% of these same reefs were threatened by human activities, especially in the Eastern Caribbean, most of the Southern Caribbean, Greater Antilles, Florida Keys, Yucatan, and the nearshore parts of the Mesoamerican Barrier Reef System. All these areas suffered severe bleaching damage in 2005. The R@R analysis indicated that coral loss could cost the region US\$140 million to \$420 million annually.

This book compiles data and observations of coral bleaching and mortality from more than 70 coral reef workers and volunteer divers to summarize the current status of reefs in the Wider Caribbean; but more importantly the book seeks to provide information to coral reef managers and decision makers to aid in the search for solutions to arrest the coral reef decline in a region that contains 10.3% of the world's reefs. These compiled reports also illustrate the value of early predictions of possible bleaching; 'products' developed by NOAA from archived

and current satellite images, complemented by direct measures like temperature loggers and buoys, were used to warn of the impending bleaching threat. The products were distributed widely through e-mail alerts and various internet sites, alerting natural resource managers of the potential for damage to their coral reefs. Hundreds of scientists and resource managers in the Caribbean used these alerts and products in 2005 to allocate large amounts of their limited financial and logistic resources to monitor what turned out to be a record-breaking bleaching event. The information yielded from this monitoring will be vital to future management efforts to protect coral reefs in light of today's rapidly changing climate.

THE 2005 CORAL BLEACHING EVENT AND HURRICANES

These following HotSpot images and the other 'Degree Heating Week' images on the front cover and inside title page are typical of the information that was widely dispersed throughout the Caribbean and elsewhere via the Internet through the coral reef information network 'Coral-List'. This generated considerable correspondence, and senior NOAA scientists have offered their personal insight of what happened in their offices as the sequence of events developed. These are detailed in Chapter 4.



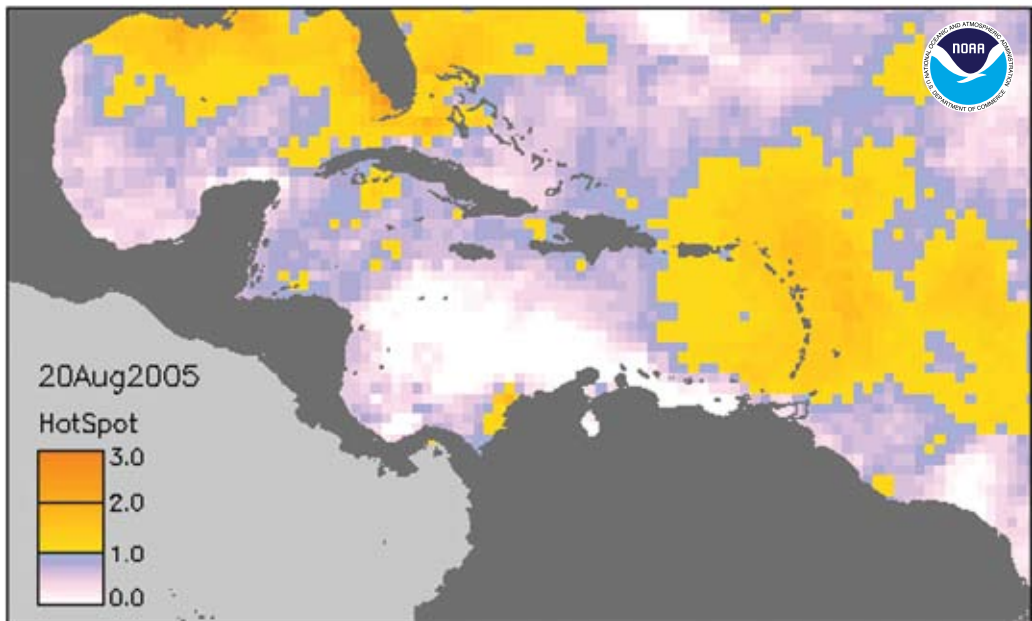
This 1st figure illustrates a typical HotSpot image (explanation on p. 38) that was generated from satellite data and distributed throughout the Wider Caribbean. The HotSpot on 16 July 2005 shows waters 1°C to 2°C above the normal summer maximum as seen as 'warm' yellow and orange colors over central America as well as a large but less warm region in the central Atlantic Ocean; as this was being reported there was evidence of bleaching reported in Belize.

The first signs of bleaching were in Brazil in March during the southern summer. However, this did not correspond to a major HotSpot; it was more likely due to a local calm weather and heating event. The first coral bleaching in the Caribbean was reported in early June on the Islas del Rosario in northwest Colombia where waters had warmed to 30°C. These waters then cooled and the corals recovered. By late June, surface waters exceeded 30°C around Puerto

Rico, and up to 50% of corals had already died. There was also bleaching on the Caribbean coast of Panama, although this did not result in significant mortality.

In July, bleaching was reported in Belize, Mexico, Bahamas and in Bermuda and the US Virgin Islands, which also coincided with reports of the death of large sponges in the US Virgin Islands and off Cozumel in Mexico.

Although between 25% and 45% bleaching was reported in Belize and Mexico, the HotSpot along the Mesoamerican Reef system dissipated with the regular passage of storms during 2005, which prevented any significant bleaching related mortality. Despite the cooling benefits to the region, Hurricanes Wilma and Emily caused considerable damage to coral reefs, especially in Mexico around the island of Cozumel. Lower mortality in the Mesoamerican region may be attributable to a reduced population of temperature sensitive corals, because previous bleaching and disease events have removed the more sensitive species. It appears that the more resistant species were only slightly affected. Coral cover has decreased markedly in the past 35 years, in some cases from near 80% to less than 20%.

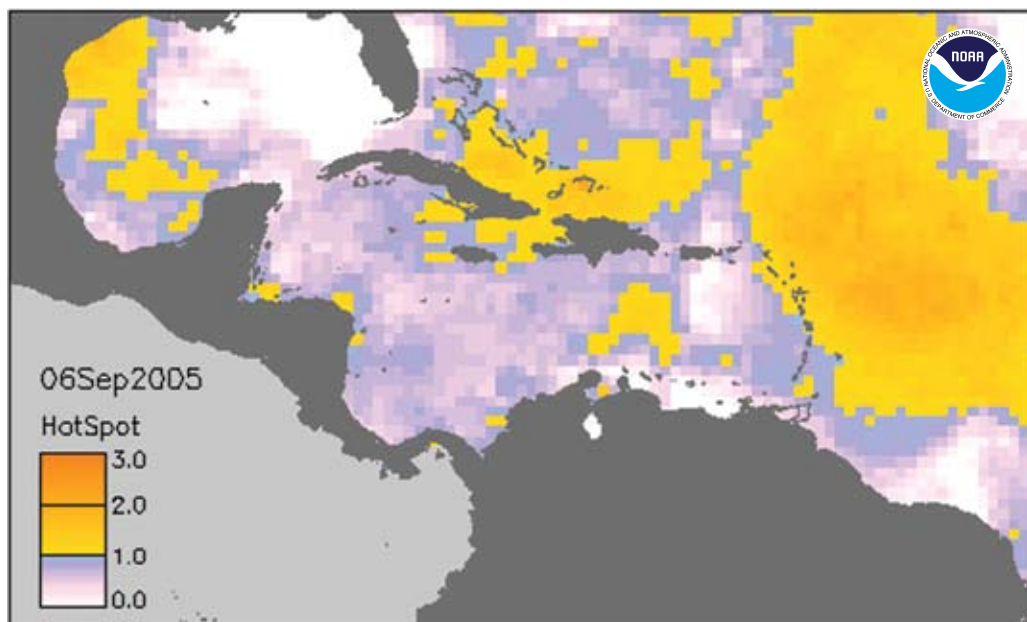


This image from mid-August shows a dramatic expansion of two HotSpots with temperatures 2°C to 3°C in excess of the summer maximum covering large parts of the Northern Caribbean including Florida, the Flower Garden Banks in the Gulf of Mexico and just touching Cuba. The HotSpot in the Atlantic has expanded alarmingly to cover all the islands of the Lesser Antilles; and there is a small HotSpot over Colombia. Bleaching was being reported in all of these regions, as outlined in the following chapters.

By early August, concern was growing that bleaching would damage the reefs of Florida and the Gulf of Mexico. As the HotSpot expanded in the north, there were reports of extensive bleaching in the Florida Keys, with water temperatures around 31°C and almost totally calm and sunny conditions. In late August, extensive bleaching coincided with the warmest water

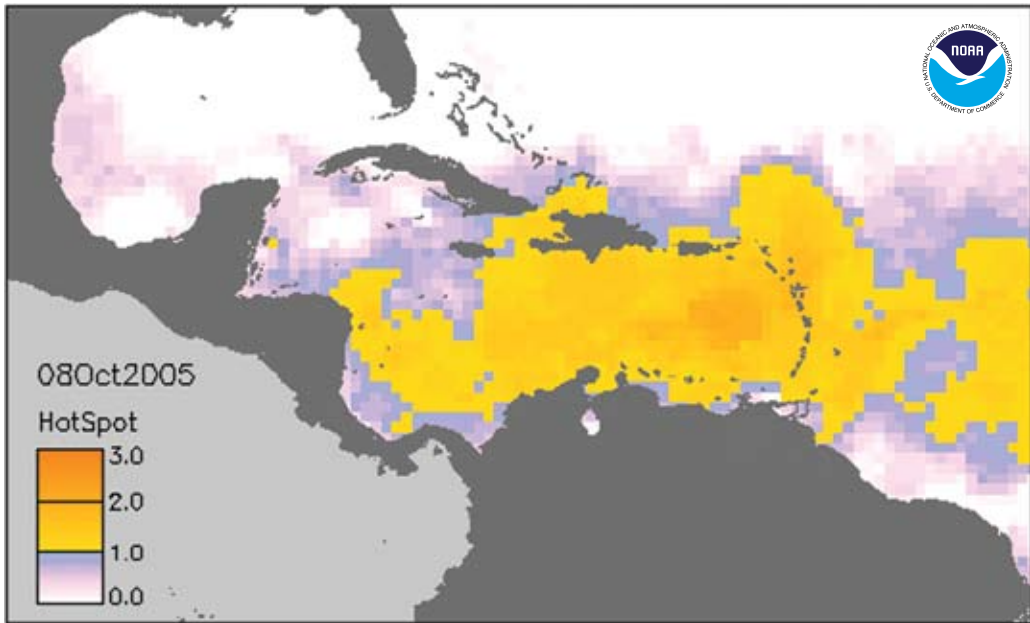
ever recorded on Sombrero Key in Florida, but fortunately for these reefs, Hurricane Katrina passed through the area as Category 1 storm resulting in considerable cooling of the waters (see p. 35).

Similarly, bleaching increased around Puerto Rico involving all corals and coral-like animals under hot calm conditions and the incidence of coral disease increased alarmingly. Severe bleaching, up to 95%, was being reported from several islands in the Greater (Cayman Islands, Jamaica, Cuba) and Lesser Antilles (Guadeloupe, Martinique, St. Barthelemy in the French West Indies, St. Maarten, Saba, St. Eustatius in the northern Dutch Antilles, and Barbados). Bleaching in the Cayman Islands was the worst ever recorded.



By early September, two major HotSpots with sea surface temperatures 2°C to 3°C more than normal are covering Puerto Rico, the Virgin Islands and the other is still covering the Lesser Antilles. The original HotSpot over the Gulf of Mexico and Florida has been effectively ‘blown away’ by Hurricanes, especially Katrina that went on to devastate New Orleans on 29 August 2005 (see the Chapter on Hurricanes p. 31). Reports of major coral bleaching were received corresponding to all the sites with HotSpots.

The weather was particularly calm for two weeks in September, and was accompanied by extensive bleaching on the south coast of Jamaica where about 80% of corals bleached. The August bleaching on the north coast of Jamaica began to subside. Sea temperatures in the U.S. Virgin Islands reached more than 30°C at 16 m depth. Bleaching affected most coral species. More than 90% of corals bleached down to 30 m on the nearby British Virgin Islands. More extensive bleaching continued on northern Puerto Rico. The bleaching footprint had expanded to include Trinidad and Tobago and the Dominican Republic reported bleaching in 85% and 68% of corals.



The peak of HotSpot activity occurred in early October with a massive area of warm water covering virtually all the central and eastern Caribbean. A series of Hurricanes had helped cool the waters of the Northern Caribbean; but there were no hurricanes to pass through the Lesser Antilles where the waters were warmest. In mid to late October the HotSpot ‘followed the sun’ southward and then bathed the Netherlands Antilles and the northern coast of South America. By early November, the HotSpot had virtually dissipated and conditions had returned to normal. However, this 4 month period of unusually warm waters had wreaked havoc throughout the Wider Caribbean as is described in the following chapters.

By October, dangerously elevated sea temperatures had been bathing the Lesser Antilles for almost 6 months; most of this time the temperatures exceeded the normal coral bleaching thresholds. This sustained thermal stress resulted in the most severe coral bleaching and mortality ever recorded in the Lesser Antilles with 25% to 52% coral mortality in the French West Indies, and the most severe bleaching event ever recorded around Barbados. Bleaching affected all coral species at all depths. In the Netherlands Antilles there was 80% coral bleaching around the islands to the north, near the British Virgin Islands, whereas around Bonaire and Curacao in the south there was only minor bleaching and virtually no mortality. Further to the east there was 66 to 80% bleaching of the coral cover on Tobago. On average, the accumulated Caribbean thermal stress during the August-November period was greater than had been experienced by these reefs during the previous 20 years combined.

A second bout of bleaching started when the HotSpot ‘followed the sun’ with Colombia seriously affected in October and the peak bleaching in Venezuela in November and December 2005. Bleaching was highly variable with sites reporting anything from zero to 100% bleaching, but the mean was closer to 25%; fortunately mortality on reefs in tropical South America was far less than on reefs to the north.

WHY CLIMATE CHANGE IS A THREAT TO CORAL REEFS

Corals bleach when the coral animal host is stressed and expels the symbiotic zooxanthellae (algae) that provide much of the energy for coral growth, and coral reef growth. Although several different stresses cause bleaching, by far the most significant cause of coral bleaching in the past 25 years has been sea surface temperatures that exceed the normal summer maxima by 1 or 2°C for at least 4 weeks. This results in excessive production of toxic compounds in the algae that are transferred to the host coral. The host coral reacts by expelling their symbiotic algae, leaving the coral ghostly white and particularly susceptible to death from starvation or disease. If conditions become more favorable, corals often recover, although they often experience reduced growth and may skip reproduction for a season. In 2005, many bleached corals did eventually die.

Coral bleaching was first noticed as a significant problem in the wider Caribbean region in 1983. Concurrently there were increases in coral disease across the region, thus the assumption was made that these were both associated with higher temperatures. The bleaching and outbreaks of infectious diseases, such as white plague, have caused such major losses in the branching staghorn and elkhorn corals (*Acropora cervicornis* and *A. palmata*), that they were added to the List of Endangered and Threatened Wildlife under the Endangered Species Act of U.S.A. in April 2007. The listing as Threatened Species requires that US government agencies maximize their efforts at conserving these species, which are the most characteristic of Caribbean reefs and were once major contributors to reef construction.

The bleaching in 2005 ‘coincided’ with major outbreaks of coral diseases which saw extensive shrinkage in the cover of live corals throughout the Caribbean. While many corals started to recover when seawater temperatures dropped with the onset of winter, coral diseases broke out and resulted in significant losses of coral cover, notably along the coast of Florida (Chapter 6), in Belize (Chapter 5), the Virgin Islands (Chapter 7), and the Lesser Antilles (Chapter 8). The accepted explanation is that bleached corals are stressed, lack reserve lipid supplies and are effectively starving, making them more susceptible to disease.

Ocean acidification is a parallel climate change threat to coral reefs that results from increased concentrations of CO₂ dissolving in seawater, which reduces its pH. This process is called ‘ocean acidification’, and by the end of this century, acidification may be proceeding at a rate that is 100 times faster and with a magnitude that is 3 times greater than anything experienced on the planet in the last 21 million years. How this will affect marine ecosystems is unknown, but impacts on marine calcifiers could be considerable. Using the pH levels expected by the end of this century, laboratory studies show a significant reduction in the ability of reef-building corals to grow their carbonate skeletons, making them both slower to grow and more vulnerable to erosion. This would also affect the basal structure of coral reef itself. While the long term consequences of ocean acidification on corals is not known, corals do not seem to be able to easily adapt to such rapid changes. All predictions from climate change models point to ocean acidification having progressively more negative impacts on corals and coral reefs.

Hurricanes and extreme weather events are also predicted to become more frequent and severe as the pace of climate change quickens. There is increasing evidence that the proportion of more destructive hurricanes has increased in recent decades, although the total incidence of tropical storms has not increased. Stronger hurricanes will result in more severe wave damage

and flooding from the land, thereby adding an additional stress to already stressed reefs. Low to moderate strength hurricanes can be beneficial during summer, however, by cooling surface waters and reducing the likelihood of coral bleaching.

There is insufficient evidence or indications that the other potential climate change stresses will result in significant damage to coral reefs. There is a potential for negative impacts from possible shifting of ocean currents or rises in UV concentrations; however these are not evident at the moment. Sea level rise will not directly threaten corals, but may render coral reef islands uninhabitable, thereby threatening coral island cultures and nations.

IMPLICATIONS OF 2005 FOR CORAL MANAGERS

Coral reef managers were unprepared for the climate-related destructive events of 1998. Many coral reef managers in the Indian Ocean and Western Pacific reported that massive coral bleaching in mid to late 1998 was devastating their coral reefs, and they asked 'what have I done wrong to cause the corals to die'. They were perplexed that corals were dying on the same reefs that they were actively managing to remove pollution, sedimentation and over-fishing stresses. The cause of the problems to their reefs was related to climate change via a particularly severe El Niño and La Niña climate switch that raised sea surface temperatures (SSTs) above levels that had ever been recorded on those coral reefs. We now know that no management actions could have prevented the extent of coral death; the only advice the coral reef research and management community could offer was that 'better managed reefs will recover more rapidly than those under human stresses'.

The events of 1998 stimulated the international coral reef community to develop advice for coral reef managers faced with similar circumstances in the future. *A Reef Manager's Guide to Coral Bleaching* was developed in 2006 to provide that advice for coral reef managers faced with stresses beyond their immediate control. The report is summarized by the authors in Chapter 10 and provides reef managers with the explanations why reefs are damaged by such climate related events and explains why some reefs resist coral bleaching and others are more resilient i.e. they recover faster after severe losses.

The report guides reef managers into steps they can take at national and global levels to raise awareness of the potential devastation that increasing global climate change, though the release of greenhouse gases, can have on coral reefs. However, the emphasis is on providing managers with practical advice on how to increase protection of those reefs that are either naturally resistant or tolerant to bleaching, assist in promoting adaptation mechanisms that enhance reef resilience, while simultaneously reducing local pressures on the reefs and nearby ecosystems to enhance chances for natural recovery. Importantly, the Guide advises reef managers on how to engage with local people and assist in maintaining socioeconomic well-being and bringing them on board to assist in the sustainable use of their coral reefs.

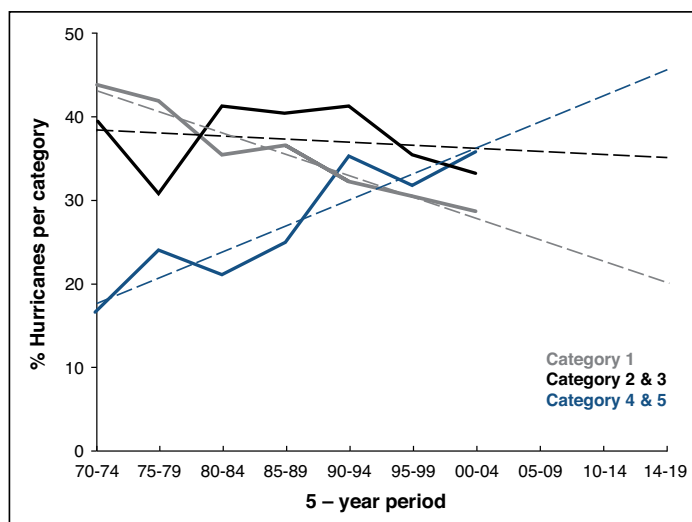
AND THE FUTURE

Sadly for coral reefs, all predictions from the Intergovernmental Panel on Climate Change (IPCC) reports in 2007 indicate that the extreme warming of 2005 will not be an isolated event (Chapter 11). It will probably happen again in the future and, when it does, the impacts will be even more severe. The IPCC concluded that human-induced climate change will warm the

world by 1.8 to 4.0°C by the year 2100. This warming will affect most of the wider Caribbean Sea making years like 2005 more common and more devastating for coral reefs.

In addition, increasing acidity in the seawater with the solution of more CO² will result in slower growth of corals that are trying to recover from bleaching and other disturbances.

One other potential consequence of the human-induced warming is an increase in the frequency of more damaging Category 4 and 5 hurricanes in the Caribbean. These storms develop as waters warm over the tropical North Atlantic and Caribbean waters. It is predicted that warmer surface waters with increased amounts of thermal energy will fuel increases in tropical storm strength. The latest predictions are for an increase in the more intense Category 4 and 5 hurricanes that will probably cause significant damage to the coral reefs and the communities that depend upon them (Chapter 3).



This figure shows the proportion of intense hurricanes has been increasing since 1970 while the total number of hurricanes has not changed much. These graphs plot all global hurricanes combined into 5 year periods from 1970 to 2004, with projected trends added to 2019. Category 1 storms are relatively weak whereas Category 5 storms are particularly devastating (adapted from Webster 2005). Dashed lines show significant linear trends.

This is a pivotal moment for the coral reefs. The world is already committed to some further warming due to past greenhouse gas emissions and the expected emissions from existing world energy infrastructure (Chapter 2). Thanks to more than a century of ‘committed warming’; events like 2005 are expected to occur more frequently by the 2030s. The only possible way to sustain some live coral on the reefs around the world will be to carefully manage the direct pressures like pollution, fishing and damaging coastal developments, and hope that some coral species are able to adapt to the warmer environment. However, a dramatic reduction in greenhouse gas emissions in the next 20 years will be critical to control further warming and higher CO₂ levels that will probably reduce the robustness and competitive fitness of corals and limit the habitats for many other organisms living on Caribbean coral reefs.

1. INTRODUCTION

The crisis facing coral reefs was only fully recognised during the last two decades. Gradual and chronic stresses have resulted in major losses of coral reefs in areas surrounding large human populations, but the pace of change was slow. Over-fishing and destructive fishing, pollution with nutrients and sediments, coral diseases, mining of coral rock and sand, and coastal developments that modified the reefs were the predominant chronic stresses damaging coral reefs around the world. However, global climate change is now a major threat to the long-term future of the world's coral reefs.

The major El Niño/La Niña Southern Oscillation (ENSO) cycle in 1997-98 resulted in massive losses of corals in the Indian Ocean and the Western Pacific. It was estimated that 16% of the world's coral reefs were effectively destroyed in about 10 months when sea surface temperatures increased considerably and killed corals in many areas, including those remote from damaging human activities.

Then 2005 was the hottest year in the world's recorded history, causing a major bleaching event in the Caribbean without a concurrent El Niño. This year surpassed 1998 and the other 8 hottest years during the past 15 years and further confirms a pattern of global climate change. This report documents the effects of raised temperatures in causing coral bleaching and mortality in the wider Caribbean in 2005 and whether the stressed corals recovered. The report also examines the effects of severe category 4 and 5 hurricanes during 2005 that also damaged coral reefs and other coastal ecosystems. Fortuitously, several of these hurricanes actually protected some reefs by cooling the waters that were causing heat stress. The damage that occurred to reefs in the Caribbean, however, has followed centuries of reef degradation from human activities.

Assessment of climate change effects on marine ecosystems requires a focus on physical observations as well as examining the organisms in the ecosystem. The National Oceanic and Atmospheric Administration (NOAA) of USA is mandated to understand the environment and ecosystem within a changing climate, and use this understanding to improve conservation and management of living marine resources and ecosystems. Thus, NOAA provides products to alert users of the potential for coral bleaching events around the world through satellite and *in situ* observations, forecasts and warning systems. NOAA also works with local and regional managers to quantify the effects of increasing seawater temperatures on coral reefs, and determine ways local managers can mitigate climate change impacts. A partnership was formed with the Great Barrier Reef Marine Park Authority of Australia, the U.S. Environmental Protection Agency, and the IUCN (The World Conservation Union) to produce 'A Reef Manager's Guide to Coral Bleaching', featured in Chapter 10. NOAA and the Department of Interior led an interagency

effort to respond to and assess the 2005 massive coral bleaching event in the Caribbean under the aegis of the U.S. Coral Reef Task Force. The effort also involved many government and NGO agencies, including local partners in Florida, Puerto Rico, the U.S. Virgin Islands, and Caribbean island nations, to assess the impacts of the 2005 mass bleaching event and make recommendations on how to prepare for and address future events.

The marine life and people in the Caribbean depend on healthy coral reef ecosystems and the services they provide, especially for tourism, fishing and coastal protection. The unprecedented and region-wide bleaching event of 2005 has, and will continue to have, far-reaching ecological and major economic implications for the region. UNEP, via the UNEP Coral Reef Unit, assists partners such as the GCRMN in collecting, assessing and disseminating comprehensive and reliable data to decision makers on the status of coral reefs. The Caribbean Environment Programme (CEP) of UNEP provides the Secretariat to the Cartagena Convention on the protection and development of the marine environment in the Wider Caribbean. UNEP CEP works closely with its 36 member governments and other stakeholders to create, harmonize and implement policies, regional cooperation and meaningful actions towards the conservation and sustainable use of coastal and marine resources in the Caribbean, including coral reefs. Local and regional activities are implemented on integrated coastal area management, strengthening of Marine Protected Areas, coral reef monitoring, control of land-based pollution, and promotion of better-practices for fishers and sustainable tourism. UNEP CEP and the Coral Reef Unit acts as the link for these countries into the GCRMN, to assist them in responding to the impacts affecting coral reefs, such as those caused by the 2005 bleaching event.

Since 2006, IUCN has hosted the Marine Working Group on Climate Change and Coral Reefs (CCCR), a widely representative collaborative initiative established with support from the MacArthur Foundation. CCCR provides a mechanism to focus scientific contributions from leading research groups, and synthesize the relevance of resilience to coral reefs and climate change. It seeks to bridge gaps between theoretical science and management application in order to fast-track the development and use of tools to improve the protection of coral reefs under the threat of climate change and interacting or synergistic human threats. IUCN also works extensively with members and partners on developing and applying better practices for ecological adaptation management, including incorporation of best practice climate change resilience principles into the design and management of regional Marine Protected Area networks and capacity building.

WWF is a global conservation organisation that views climate change as a significant threat to coastal ecosystems and livelihoods, and is working to develop adaptation strategies to build ecosystem resilience and improve the ability to cope with a changing climate. Within the Mesoamerican Reef Ecoregion, WWF and partners are working to reduce direct human threats to reefs (e.g. collaborating with agroindustries and local farmers to reduce agrochemical use and working with fishermen on sustainable fishing practices) while concomitantly implementing critical steps towards building reef resilience. Through collaboration with partners, WWF assessed the Mesoamerican Reef System in 2006 to ascertain overall reef status and promote protection of bleaching resilient and resistant reefs. WWF is also working on strategies to build social networks for adaptation, including: improved communication, awareness and public outreach; climate witnesses (for local and international outreach); training and capacity building for WWF staff and local counterparts; and climate change policy recommendations (e.g. Government of Belize adaptation strategy) based on local consultation.

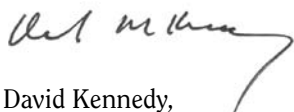
The Intergovernmental Oceanographic Commission (IOC) of UNESCO provides an intergovernmental forum to catalyze and coordinate research on coral reef ecosystems. The IOC sponsors international science required to answer management questions: the causes of coral reef degradation; the global status of coral reef health; the predictions of impacts (both ecological and socioeconomic); and actions to minimize impacts or adapt to changes. The network of 136 Member States is used to communicate the results of these programs to stimulate coordinated action at local, national, and global levels. The IOC sponsors: the Coral Bleaching Working Group of the GEF / World Bank Coral Reef Targeted Research and Capacity Building Project; the Ocean in a High CO₂ World symposium series (assessing current knowledge on ocean acidification impacts on marine ecosystems); the Global Coral Reef Monitoring Network; and has worked recently with UNEP and the Census of Marine Life to report on the vulnerability of deep-sea corals to fishing on seamounts beyond areas of national jurisdiction. They also work with other programs within UNESCO dealing with coral reef issues, such as the Coasts and Small Islands Program and the World Heritage Center's Marine Program.

The emergence of climate change was recognised as an over-arching threat to tropical marine ecosystems at the 3rd International Tropical Marine Ecosystem Management Symposium (ITMEMS) in Mexico, 2006. This meeting was coordinated by the International Coral Reef Action Network (ICRAN) to facilitate discussion and information sharing on coral reef resilience and management, and particularly to communicate climate related challenges for managers (the ICRI statement on climate change is discussed in Chapter 10). ICRAN encourages natural resource management to increase the resilience of coral reef ecosystems through effective implementation of marine managed areas, and the promotion of networks of managed areas. ICRAN is partnering with the World Resources Institute on a global analysis of threats to reefs, including vulnerability of coral reefs and associated communities to bleaching, and the economic impacts of reef degradation.

Conservation of coral reefs in the face of increasing global warming will require that all relevant people are informed and encouraged to take remedial action. This is why volunteer and community based organisations like Reef Check and the PADI Foundation are critical to successful action. Reef Check has been working with the GCRMN to monitor coral reefs using a standard method since 1997 and now has teams in over 90 countries. The goals include tracking the impacts of climate change as well as to conserve remaining coral reefs. This important report documents the serious impacts of the 2005 bleaching event in the Caribbean and includes data collected by Reef Check teams in collaboration with NOAA. These data reveal interesting differences in the effects of a major bleaching event on reefs in the Caribbean compared with the Indo-Pacific and provide hope that some reefs may be more resistant than others to temperature stress.

This book collates considerable data and information gathered by NOAA staff, and other coral reef researchers and managers in the Caribbean. These reports will help clarify our understanding of how global climate change is affecting coral reefs and other tropical coastal ecosystems. The final chapter in this book draws on climate change models to attempt predictions in the short to medium-term for the wider Caribbean. This report also illustrates the importance of supporting the GCRMN and partners in monitoring reefs and preparing plans for a warmer world.

We represent organisations that are working towards the sustainable use and conservation of coral reefs around the world, and request that governments, organizations and people actively participate in the International Year of the Reef in 2008 to promote education, research and public awareness about the value of coral reefs and threats to their health. We, and the thousands of people we represent, call on all people to acknowledge that global climate change represents a serious and increasing threat to the integrity of the coral reefs of the world, and seek mechanisms to ameliorate the effects and reduce future impacts. Thus, we are pleased to endorse the GCRMN report 'Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005.'



David Kennedy,
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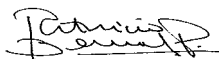
Nelson Andrade Colmenares, Coordinator
United Nations Environment Programme, Caribbean Environment Programme



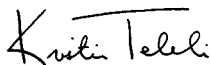
Carl Gustaf Lundin,
Head, Global Marine Programme, IUCN – The World Conservation Union & Chair, GCRMN
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Simon Cripps
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Patricio Bernal,
Executive Secretary, Intergovernmental Oceanographic Commission of UNESCO



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2. CORAL REEFS AND CLIMATE CHANGE: SUSCEPTIBILITY AND CONSEQUENCES

JOAN KLEYPAS AND OVE HOEGH-GULDBERG

SUMMARY

- Coral reefs, both tropical and deep cold water, are global centers of biodiversity that are being damaged by a combination of direct human impacts and global climate change.
- The major threats associated with climate change are increasing sea temperatures and increasing ocean acidity as a result of rising atmospheric carbon dioxide (CO₂), as well as a predicted increase in storms.
- Higher than normal sea surface temperatures cause increased stress to corals and result in coral bleaching, and frequently in mortality. We have a better understanding of why the apparently stable symbiosis between corals and their symbiotic dinoflagellate (zooxanthellae) algae breaks down. Bleaching results in the loss of the algae and a reduction in the coral's energy producing systems; severe stress often results in coral mortality.
- Increasing concentrations of CO₂ lower the pH of seawater, which reduces the capacity of corals and many other marine organisms to make calcium carbonate skeletons because of a coincident decrease in the concentration of carbonate ions.
- These threats acting in combination with local factors, such as declining water quality and over-fishing, will reduce the resilience of coral reefs, and change reef structure and community composition. The result will reduce biodiversity through large-scale loss of functional reef ecosystems and the many other organisms that depend on them.
- Action to conserve these reefs is now urgent and must include global and local strategies via the implementation of strong policies for reductions in greenhouse gas emissions and effective management of local stresses that are also damaging coral reefs.

INTRODUCTION

Tropical coral reefs are probably the most sensitive marine ecosystem in the world to global climate change. Reefs are already being devastated by the consequences of climate change, and will probably suffer particularly serious damage in the next 10 to 20 years. This chapter seeks to answer the questions: 'Why are coral reefs particularly susceptible to global climate change?' and 'What consequences will flow from this sensitivity to changing environmental conditions?'

The following possible impacts on coral reefs will be examined in this Chapter:

1. Rising sea surface temperatures;
2. Increasing concentrations of CO₂ in seawater;
3. Sea level rise;
4. Possible shifting of ocean currents;
5. Associated rises in UV concentrations; and
6. Hurricanes and cyclonic storms.

This chapter focuses on the tropical shallow water corals that live in symbiosis with dinoflagellate algae. However, there are vast areas of deep-sea corals that live at great depths in dark, cold waters. These vast and complex ecosystems were largely unknown until very recently, but there are serious concerns that global climate change will result in major damage, especially through increasing concentrations of CO₂ in seawater (see the Box below).

Coral reefs are particularly long-lived and highly evolved ecosystems. Tropical reefs are technically shallow water calcium carbonate deposits that arise from the activities of marine organisms. They have existed in one form or another for more than 650 million years. The major organisms that constructed reefs in the past have included algae, corals, calcified sponges (such as the now extinct 'archaeocyathids' and 'stromatoporoids'), bryozoans, bivalves and crinoids. The ancestors of modern-day stony (scleractinian) corals first appeared about 250 million years ago, during the Triassic, and flourished as the prominent reef builders for many periods during the more recent Jurassic (190–150 million years before present) and Cretaceous (150–65 mybp). Like other ecosystems, they were disrupted by the mass extinction events caused by meteors and volcanic eruptions that also resulted in major climate changes. The Cretaceous-Tertiary extinction event 65 million years ago resulted in the extinction of many coral species, but corals eventually re-established their position as the dominant reef-builders about 36 million years ago (Oligocene). There is strong evidence that the beneficial symbiosis that these reef-building corals developed with dinoflagellates (the zooxanthellae) arose about that time and may be a major reason for their success. The last major disruption to reefs, or at least a shrinking of their habitat, was the ice age between the Pleistocene (last period) and the Holocene (current period) when sea levels fell between 110 and 120 m, exposing the shallow living reefs to the air, thereby 'forcing' reefs to grow downwards on near vertical continental slopes. When that ice age ended at the start of the Holocene, sea level rose rapidly and by about 8000 years ago had flooded the continental shelves, thus greatly expanding the area for modern coral reef growth.

Coral reefs have a number of special features that have allowed them to develop over these long periods. Corals, calcareous algae and other reef-dwellers that secrete calcium carbonate develop the reef base that supports the entire ecosystem. It is the reef structure itself that

provides the complex habitat that supports high biodiversity. The features of tropical coral reefs outlined below, are those pertinent to global climate change:

- Corals contain photosynthetic symbiotic dinoflagellate algae, 'zooxanthellae', that provide them with abundant energy and assist in nutrient recycling, allowing them to survive in generally low nutrient tropical and sub-tropical oceans;
- The large amounts of energy made available to the corals by zooxanthellae enables rapid growth and skeletal development, thereby assisting them to compete effectively with other organisms such as sponges and macroalgae (seaweeds);
- Many corals currently live near their maximum temperature tolerance. This aids more rapid biochemical reactions, but it leaves them vulnerable to small perturbations in temperature;
- Coral reefs occur in the shallow parts of the photic zone, although they often occur as deep as 60 m in clear waters. Their distribution into more temperate zones may be limited to progressively shallower habitats at higher latitudes, primarily because of light limitations in winter;
- The habitat complexity that provides niches for many reef animals and plants depends on the morphological structure of many corals; e.g. branching coral species provide a structurally complex habitat, whereas massive corals provide a solid, stable base. Thus, selective elimination of certain types of species will have repercussions across the community;
- Many animals (e.g. fish, crustaceans, worms) depend on corals for both habitat and food. Many of these have co-evolved complex symbioses; e.g. gall crabs and some fish (damselfish, butterflyfish, and some gobies) only live on a few coral species.

While coral reefs are long-lived and relatively resilient structures, they are still sensitive to disturbance such as excessive wave action, changes to the clarity of the water through excess sediment input resulting from damaging human activities, pollution and the effects of over-fishing. Now global warming and ocean acidification are developing as additional major threats to their future viability, with some of the first impacts already being felt.

The predominant threats associated with climate change are increasing sea surface temperatures and ocean acidity, sea level rise, and the potential for weather changes, including more frequent and intense cyclonic storms. In addition, climate change will involve other stressors such as the increased incidence of disease in coral colonies weakened by bleaching, possible shifting of ocean currents and rises in the incident UV radiation associated with some greenhouse gases that also deplete atmospheric ozone.

1. RISING SEA SURFACE TEMPERATURES

Sea surface temperatures have been steadily rising in tropical/subtropical waters; e.g. they rose by an average of 0.3°C between the 1950s and 1990. It is likely that reef-building corals are now 1–1.5°C closer to their upper thermal limits than they were 100 years ago, with the result that warmer than average years, arising as a result of natural variability, now push corals beyond their upper thermal thresholds. Sustained temperatures as little as about 1–2°C above the normal summer maximum are sufficient to stress corals, and cause them to bleach. Bleaching is a generalized response to stress that could arise because of changes to the physical and chemical

environment. When sea temperatures exceed the summer maximum by approximately 2–3°C for about 4 weeks under clear tropical skies, corals bleach; that is, they usually expel their brown symbiotic algae and reveal either the pale pastel colors of the host pigments, or bleach brilliant white.

We understand some of the mechanisms behind the temperature stress responses of corals. Thermal stress damage starts in the photosynthetic system of the symbiotic zooxanthellae, causing a collapse of the light processing mechanisms, such that the excess light is diverted from normal photosynthesis to producing excess free oxygen radicals. These are toxic to the coral and the symbiosis falls apart, resulting in the corals ejecting the algae, their major source of energy. While the first damage is to the photosynthetic mechanisms of the algae, other aspects of the coral-zooxanthellae symbiosis are also damaged. Thus, many corals are highly sensitive to changes in sea temperature.

Bleached corals may recover their symbiotic zooxanthellae if the temperature stress is mild or short-lived; but if it is more intense or long-lived, corals begin to die or they may be affected in other ways. For example, reproduction and growth may be affected for up to two years after a bleaching event, thus frequent bleaching events will have major impacts on the corals and the reefs they build. Evidence from the field also indicates that stressed corals are more vulnerable to pathogens that may occur on the outer cell surface layer, resulting in more disease in such colonies.

Corals around the world have developed upper thermal thresholds that are close to local maximum temperatures; corals that live in cooler waters at higher latitudes will bleach at much lower temperatures than corals in warmer, more tropical waters. These differences are the result of past adaptation (evolution) to the local temperatures by corals over thousands of years. The rates of sea temperature changes predicted by models of global climate change indicate that coral bleaching will be more frequent and severe in the future. Bleaching was virtually unheard of 30 years ago; now bleaching occurs in some places as frequently as every 3–4 years and could become an annual event in the near future.

Why most potential adaptation mechanisms will not work: A core assumption in the predictions of rapid reef decline is that there will be insufficient genetic change in the corals to keep pace with climate change. The thermal stress thresholds of corals have been relatively stable over several decades and have shown no tendency to shift upwards. However, bleaching and mortality are increasing, which indicates that stress thresholds are not changing rapidly enough to prevent bleaching in rapidly warming seas.

One alternative hypothesis is that corals, via their symbiont zooxanthellae, may evolve rapidly through the acquisition of more thermally tolerant symbionts. If new symbiotic relationships can be rapidly formed within a few decades, corals will become more thermally tolerant, allowing them to keep pace with rapid climate change. Unfortunately there is no evidence that corals can form new symbiotic relationships easily, or that thermal tolerances will rise sufficiently to protect coral reefs from bleaching. No lasting changes have been observed in coral-zooxanthellae partnerships before and after major bleaching events.

The 2007 Intergovernmental Panel on Climate Change Report (IPCC 4th Assessment Report) predicts that climate change will continue for hundreds of years, with increases in greenhouse

gases such as CO₂. Current predictions of future coral reef bleaching events indicate that corals will not adapt to warmer water without either a stabilization of greenhouse gas emissions or even a decrease. If low emission technologies result in global temperatures stabilizing at 2°C above the present, coral populations will initially decrease with the loss of temperature sensitive species, until they are replaced by more temperature resistant species. That will take decades if not centuries. However, if greenhouse gases do not stabilize, the most likely scenario is that coral populations will decrease, with growing rates of extinction of corals and the thousands of other species that depend on coral reefs. This will mean an end to the all-important ecological services provided by coral reef ecosystems.

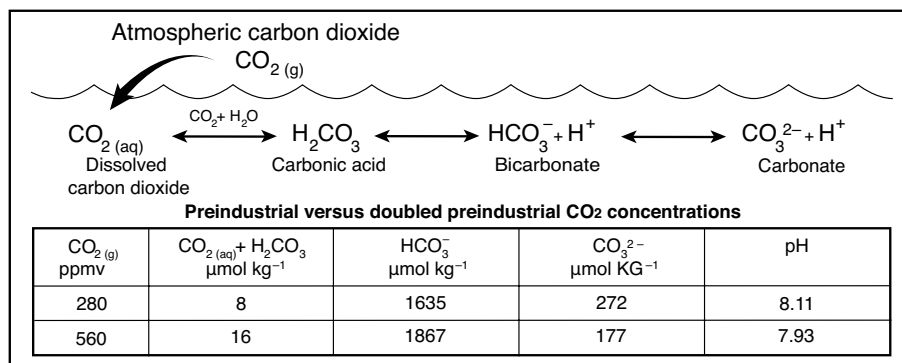
2. INCREASING CONCENTRATIONS OF CO₂ IN SEAWATER

The cascading effects on ocean chemistry of rising atmospheric CO₂ levels are referred to as ‘ocean acidification’. This does not generally invoke the same sense of urgency as coral bleaching, probably because:

- it is a creeping environmental problem;
- ocean acidification has only recently been accepted as a reality (partly because seawater carbonate chemistry is not intuitive); and
- the process is relatively invisible and does not appear to physiologically harm adult corals.

How ocean acidification will affect all life stages of organisms, reef communities, and reef structures, however, is largely unstudied. While the nature and rate of ocean acidification is well-known and predictable, the potential ecosystem effects of ocean acidification constitute a problem of high uncertainty, but high risk.

The uptake of atmospheric CO₂ by the oceans is a double-edged sword. So far, the oceans have absorbed about a third of the excess CO₂ released into the atmosphere from burning fossil fuels and other human activities. Another third has been taken up by activities on the land, and the remaining third has remained in the atmosphere such that the concentration of CO₂ has gone from 280 parts per million by volume (ppmv) before the industrial revolution to about 380 ppmv today. Ocean uptake of CO₂ from the atmosphere reduces the severity of the greenhouse effect and climate change (and indeed the conditions that cause coral bleaching). Unfortunately, it also alters the chemistry of seawater resulting in lower pH (‘ocean acidification’) and decreased carbonate ion concentrations. Low pH values represent high hydrogen ion concentrations and more acid conditions, and high pH values represent low hydrogen ion concentration and alkaline conditions. pH is reported on a logarithmic scale; such that a 1.0 change in pH represents a 10-fold change in hydrogen ion concentration. The pH of tropical seawater has remained around 8.2–8.3 for about a half million years, but will decrease to around 7.9–8.0 when atmospheric CO₂ concentrations are double the pre-industrial levels; that represents about a 30% increase in hydrogen ion concentration. This change in ocean acidity will also cause a shift in the relative proportions of the inorganic forms of carbon: dissolved CO₂; bicarbonate; and carbonate. A lowering of seawater pH also means that the carbonate ion concentration will decrease by more than 30%. This represents a substantial change in the chemical conditions supporting calcification, because the carbonate ion is a major skeletal building block for the calcium carbonate (CaCO₃) skeletons of corals and other reef-building organisms.



This diagram illustrates what will happen to ocean chemistry as more CO₂ dissolves in seawater. When CO₂ concentrations in the atmosphere effectively double from the pre-industrial levels, there will be an increase in dissolved bicarbonate and a decrease in the available carbonate in seawater. Thus it will become more difficult and energy consuming for coral reef animals and plants to make skeletons.

DEEP-SEA CORALS AND OCEAN ACIDIFICATION

Most people are familiar with tropical coral reefs, but many are unaware of the wide distribution of deep-sea corals that live in cold waters below the photic zone, in depths of 50-1000 m. The scientific world was unaware of the vast expanses of ‘deep-sea coral bioherms’ that occur along the edges of continental shelves until a few decades ago, when underwater mapping by remote cameras came into common use. These coral ecosystems are known to support many fisheries, particularly in the North Atlantic Ocean and off the coast of Alaska. A major threat to these communities has been bottom trawling, which physically destroys these slow-growing reefs. Now the global problem of ocean acidification is threatening their existence.

Deep-sea corals are considered to be particularly sensitive to ocean acidification because they often grow just above depths where waters become under-saturated with calcium carbonate. As CO₂ concentrations rise and ocean acidification proceeds, that depth is ‘migrating’ upwards, and many deep-sea coral ecosystems will soon be immersed in under-saturated waters. Since the distribution of cold water corals today appears to be limited to depths above the saturation depth, it is likely that the deeper coral ecosystems will disappear.

Guinotte JM, Orr J, Cairns S, Freiwald A, Morgan L, George R (2006). Will human-induced changes in seawater chemistry alter the distribution of deep-sea scleractinian corals? *Frontiers in Ecology and the Environment* 4:141-146.

The significance of these changes: Experiments with corals and coral communities cultured in predicted future seawater chemistry conditions show that calcification rates will decrease by 20–50% of pre-industrial levels by 2050 (the predicted date for a doubling of atmospheric CO₂ concentrations). However, there will be variations in calcification rates between species, and

particularly between major organism groups. This will depend on where calcification occurs (e.g. intracellular versus extracellular), and the biological mechanisms of calcification. A puzzling aspect of biological calcification is that corals and other calcifying organisms have the ability to isolate calcifying fluids and strongly control the chemistry of those fluids. Why will the chemistry of the external seawater strongly affect the calcification rates? There are several hypotheses on the coupled nature of calcification and photosynthesis, but no hypothesis has been fully accepted by the science community.

Coral calcification is not only determined by seawater carbonate chemistry, but also by other factors such as temperature, light and nutrients. Evidence that coral calcification rates are declining is now appearing in the scientific literature although some studies up until the early 1980s recorded a rise in calcification over the majority of the 20th century. The increase is probably a result of global warming, because many coral species calcify faster in warmer waters. Coral calcification rates increase with rising temperatures to some optimal temperature, which is near the summer maximum. Calcification then declines when temperatures exceed this maximum. This appears to have been happening over the past 15 years, during which time calcification rates have started to decline, most probably because of the combined impacts of increasing thermal stress and the reduced availability of carbonate ions.

Our understanding of how rises in atmospheric CO₂ will affect seawater chemistry has greatly improved over the last decade. There is little doubt that the carbonate system in seawater is changing according to predictions, and evidence is mounting that calcification rates will decrease, and carbonate dissolution rates will increase. The main area of uncertainty relates to how changes in calcification and dissolution will affect an organism's fitness and survival. Several functions of CaCO₃ precipitation have been proposed, but there have been few studies to test how they affect the organism or the community. Some coral species grown under extremely high CO₂ levels completely lost their ability to secrete skeletons; but regained their skeleton-building ability when conditions returned to normal. This is hopeful news that some coral species can survive without their skeletons, but even if 'naked' corals survive they will not retain their original ecological functions and roles within coral reef communities.

Coral reef ecosystems are unique because the excess production of calcium carbonate results in building the reef; the very basis of a coral reef habitat. As calcification rates decline and dissolution rates rise, the balance between reef growth and reef destruction will also change. Reefs that already have a low surplus of carbonate production, e.g. those at high latitudes, may shift from net reef building to net reef loss, and lowered calcification rates will reduce the ability to keep up with rising sea levels.

3. SEA LEVEL RISE

The 2007 4th IPCC Report suggests that there will be a rather modest sea level rise of 20–60 cm by 2100, principally caused by thermal expansion of the oceans but including some melting of glaciers and ice caps. However, the authors of this report acknowledge that the models did not include processes related to increased ice flow. It is also important to realize that the inherently conservative consensus opinion of the fourth assessment report of the IPCC does not include some of the perspectives of the expert committee on sea level. When these opinions are included, the prospect of much higher sea level rise over the 21st century becomes a greater reality. For example, continued melting of the Greenland ice sheet could cause an additional

The list below details some of the functions of Calcium Carbonate skeletons in reef-building organisms.

Function	Description
Protection	Skeleton protects organism from predators, strong hydrodynamic conditions, sedimentation, etc.
Enhances photosynthesis	In photosynthetic calcifiers, calcification releases protons that converts bicarbonate to CO ₂
Light modification	CaCO ₃ skeleton enhances light field for photosynthesis by focusing and reflecting light
Reproduction	Colony size sometimes determines fecundity or age of reproductive maturity; rates of fragmentation may be affected by skeletal density
Anchoring to substrate	Secures the organism to the substrate, may also affect initial settlement of recruits
Extension above the bottom	Upward growth limits time that an organism is subjected to bottom sedimentation or scour
Competition for space, light and other resources	Many reef-builders compete for space and light by growing faster than their competitors

rise of a meter or more this century, and with complete melting, an additional 6–7 m rise in sea level over the next few centuries. Such rises would not normally pose problems for most coral reefs; indeed sea level rise provides more space for corals to grow upwards without being exposed to the air.

There will, however, be major problems for islands and low lying coastlines. Coral cays develop via a combination of winds and waves concentrating carbonate sediments; seeds and vegetation carried in by winds and birds help to consolidate these sediments. The combination of sea level rise and possibly more tropical storms will counteract any accretion. A reduction in carbonate production because of ocean acidification will add another negative factor. Many of these coral islands and atolls in the Pacific and Indian Oceans, and in the wider Caribbean will become uninhabitable as seawater washes over the islands during storm surges, penetrates into the fresh groundwater and disrupts food crops. There are no predicted mechanisms for the sand on these islands to build up sufficiently rapidly to keep up with expected sea level rise; therefore human populations will be displaced and parts of some countries including the Bahamas and Colombia, and whole Indo-Pacific states such as Tuvalu, Kiribati, the Marshall Islands and the Maldives may cease to exist.

4. POSSIBLE SHIFTING OF OCEAN CURRENTS

We have a good understanding of how coral reef ecosystems will be affected by ocean warming, acidification, and sea level rise; however, we know less about other factors associated with climate change. Changing climate conditions may cause oceanic currents to slow or even change direction; and large scale events such as the El Niño Southern Oscillation may change in frequency and/or intensity. Given that currents connect coral reefs to other coral reefs and related marine ecosystems, these changes could have profound effects on the sustainability and management of coral reef ecosystems.

5. ASSOCIATED CHANGES IN UV RADIATION INTENSITY

The incidence of UV radiation in the tropics is usually very high, particularly in passing through the clear waters bathing coral reefs. Most coral reef animals have evolved structural, chemical and behavioral mechanisms to cope with UV radiation. Thus, no major problems are anticipated with predicted thinning of the ozone layer and a likely increase in UV radiation. Shifting ocean currents and sediment input may cause changes in the clarity of the water column, which will change visible and UV radiation penetration.

6. WEATHER, HURRICANES AND STORMS

Global climate change predictions all emphasize greater variations in weather, such as more intense periods of rainfall followed by longer periods of drought. Such climate changes over land will affect runoff and sedimentation (which are also affected by land-based human activities), and affect water quality on many reefs. More extreme rainfall events, for example, will intensify flooding and river-plume damage to reefs, while a decrease in rainfall should lead to improvements in water quality. Tropical cyclonic storms have become more frequent and intense in some regions such as the Caribbean since about 1970, with some evidence that this is fuelled by warmer oceans. Climate models predict that cyclones are likely to be more intense, with more category 4 and 5 storms; but the number of storms may not necessarily increase (see Page 14). Strong storms can cause massive damage to coral reefs; for example Hurricane Andrew in 1992 severely damaged the coral reefs in Florida and other parts of the Caribbean through violent wave impacts. A rise in storm intensity or frequency may put reefs into a permanent state of recovery, because it takes about 10–15 years for a reef to recover from a major storm. How stronger storms are likely to affect reefs is reviewed in the next chapter.

SYNERGIES, CONSEQUENCES AND OPPORTUNITIES FOR MANAGEMENT INTERVENTION

Corals build the framework of coral reefs and therefore support thousands of other species. Many of these are totally dependent on corals for food, shelter and reproduction, and will disappear with a loss of coral. Other reef organisms rely only partly on the corals, perhaps needing only the complex structure for survival. The loss of coral will result in some local extinctions and reduced diversity of fish species. For example, some fish species are more sensitive than others, with corallivorous (coral eating) species being the most sensitive; herbivores may actually multiply because there will be more algae to eat. It is probable that many of the large food fish and visiting pelagic fish will not be markedly affected, but our knowledge of these systems is not sufficient to predict which species will or will not show changes with climate change. Several recent estimates suggest that as much as 50% of the fish diversity currently on coral reefs will disappear if coral communities are severely damaged.

An understanding of how coral dependent organisms on reefs will change with the loss of corals is still being developed. However, given the extremely tight relationships between organisms and corals, the loss of corals will almost certainly be accompanied by the loss of many thousands of species. It is also important to realize that corals may not have to completely disappear to cause big effects on the organisms that use them as habitat. For example, some coral dwelling species may require dense coral populations to enable them to live close enough to the opposite sex for reproductive success.

Some climate change impacts, particularly in combination with other influences, will likely reduce the overall resilience of coral reefs. Changes in a coral community (such as reduced biodiversity) may severely undermine system resilience, resulting in a phase shift to a non-coral reef community. For example, the loss of some fish and invertebrates may leave a coral reef more susceptible to episodic outbreaks of pests or invading species. Effects like this tend to be unpredictable, but such unpredicted changes are likely to increase.

Climate change also affects coral reefs in another, fundamental way that is unique to this ecosystem; that is the effects on the geological reef structure itself. Reduced coral cover (e.g. from coral bleaching) coupled with lowered calcification rates and increased dissolution rates (ocean acidification) will reduce the net calcium carbonate production rates on reefs. By the end of this century, the overall balance of carbonate production on many reefs is expected to decline to the point where reef-building may cease or reverse. In addition, any ecosystems that are influenced by the reef structure and reef sediment production will also be affected. These could include mangroves, seagrass beds, and low-lying coral cays. It might also have significant implications for human infrastructure on coastlines protected by coral reefs.

Against the background of these dire predictions facing coral reefs, implementing management of local damage may seem irrelevant unless the current growth in greenhouse gas emissions is constrained. Even with drastic reductions in CO₂ concentrations, there will be changes and challenges for coral reefs. However, after the massive coral bleaching in 1998, coral reefs recovered better and more rapidly where stresses related to poor water quality and over-fishing were well managed. For example, where grazing fish are retained on a reef, corals will repopulate damaged areas 2–3 times faster than on over-fished reefs; similarly, growth rates of corals are faster in non-polluted waters. Managing local stresses on reefs may not prevent damage from climate change, however it will enhance recovery.

Recent evidence indicates it is imperative that there is strong action on reducing greenhouse emissions to ensure that we don't exceed much more than 450-500 ppm CO₂ in the atmosphere. Any response, however, must include local strategies to increase the effective management of local stresses, such as declining water quality and overfishing, damaging coral reefs. Reefs will persist longer under the stresses of the next 50–100 years if they are given the best chance of recovering from the inevitable ecological shocks; this will 'buy time'. These two approaches, decreasing emissions and increasing protective management, are an integral part of effectively addressing the current coral reef crisis and are discussed in Chapter 10, p. 115.

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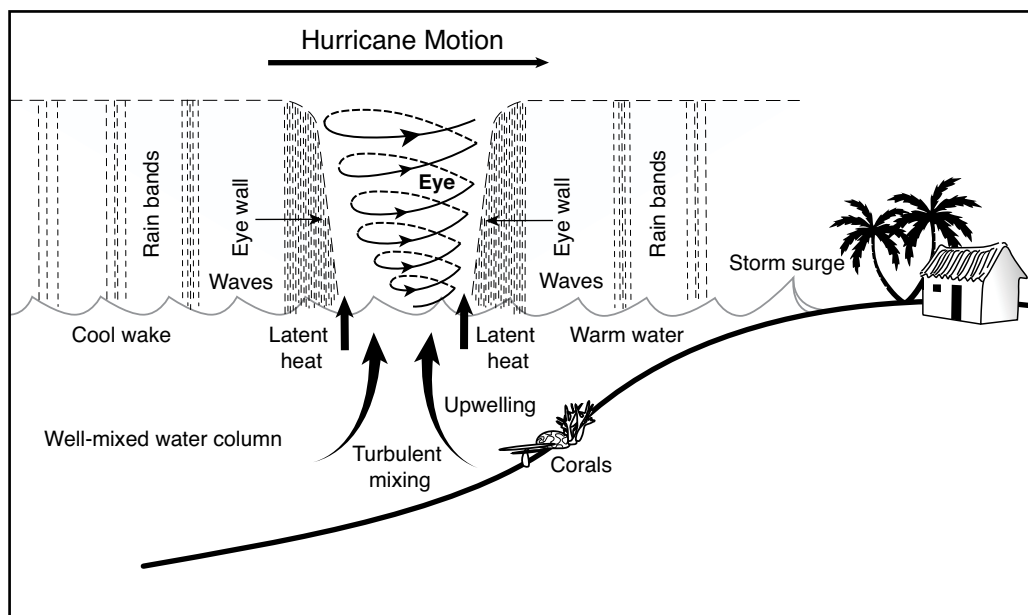
3. HURRICANES AND THEIR EFFECTS ON CORAL REEFS

SCOTT HERON, JESSICA MORGAN, MARK EAKIN AND WILLIAM SKIRVING

BACKGROUND TO HURRICANES

A hurricane (also tropical cyclone, typhoon) is a warm-core, low-pressure system that develops over tropical or subtropical waters. Most hurricanes form from a trough of low-pressure, over ocean surface temperatures greater than 26°C. As air moves across the ocean surface, it extracts moisture (water vapour) and energy (as a result of evaporation) from the ocean. The low pressure draws air inward, causing the water vapour to rise, cooling as it rises. When the vapour condenses to form clouds, it transfers the heat energy to the surrounding air. As the warm air rises higher in the atmosphere, it lowers the pressure at the ocean surface. This causes more air to enter at the ocean surface, which creates stronger winds and continues to transfer heat from the ocean into the atmosphere. As long as the atmospheric conditions are favourable and the ocean can provide the energy, this creates a feedback mechanism to strengthen the hurricane.

When fully-formed, hurricanes are well organised with a calm eye at the centre surrounded by an eye-wall where the strongest winds and most of the ocean heat extraction occurs, as illustrated in the figure below. Several rain bands can encircle the eye, also extracting smaller amounts of heat from the ocean. As a hurricane moves, it typically leaves a cool wake behind it (see ref. 3.) and pushes waves out in all directions. If a hurricane approaches land, these waves steepen and water piles up in the shallows, often pushing up onto the land. This phenomenon is called a storm surge and can be particularly damaging if it occurs during high tide. The greatest surge is usually generated in front of and to the right of a northern hemisphere hurricane (left front quadrant in the southern hemisphere).



This diagram illustrates how a hurricane forms over warm ocean waters and starts spinning in a counter-clockwise direction in the Northern Hemisphere. Large storm waves may result in significant coral reef damage. However, a hurricane will also cool surface waters and can often mitigate coral bleaching.

While there is a minimum ocean surface temperature for hurricanes to form, the energy that drives a hurricane is supplied by the upper section of the water column, not just the surface. Hurricane intensity is more closely linked to the ocean heat content than to surface temperature alone (4.). Once the eye of a hurricane moves over land it experiences greater friction and loses its source of moisture and heat, causing it to weaken. Hurricanes can also weaken at sea if their energy source is reduced by encountering cool waters (fronts, upwellings), or their vortex development is inhibited by entering a zone of high vertical wind shear.

Hurricanes help to regulate the earth's temperature, extracting heat from the ocean and redistributing it into the atmosphere; thereby moving tropical heat poleward. In the absence of regular hurricanes, tropical oceans retain more heat, which can then lead to larger, more intense hurricanes. Recent increases in ocean temperatures, very likely due to human-induced climate change, have seen tropical storms becoming stronger but not necessarily increasing in number (7. and Executive Summary p. 14).

Globally averaged land and ocean temperatures in 2005 were the highest on record according to NOAA and NASA analyses, with temperatures slightly warmer than in 1998. The 2005 hurricane season in the Atlantic and Caribbean was unprecedented, experiencing more than twice the annual average of named tropical storms over the past century and the greatest number of hurricanes in recorded history. While some of this may be attributed to improvements in hurricane observation skills through satellites and other instruments, there can be no doubt that 2005 was an extreme year for storm activity.

Hurricanes are classified by their wind speed in the well-known Saffir-Simpson scale. Category 1 storms have sustained wind speeds greater than 64 knots (33 m/s) and generally cause only minor damage upon landfall; Category 5 hurricane winds exceed 135 knots (69 m/s) and can devastate structures with both winds and storm surge.

Hurricane Category	Impacts
1	Wind 64-82 knots, storm surge 1.0-1.6 m, no real damage to building structures, damage to trees
2	Wind 83-95 knots, storm surge 1.7-2.5 m, some roofing and window damage, considerable damage to trees
3	Wind 96-113 knots, storm surge 2.6-3.8 m, some building damage, large trees blown down
4	Wind 114-135 knots, storm surge 3.9-5.5 m, complete removal of some roofs, extensive window damage, most trees blown down
5	Wind 136+ knots, buildings fall over, storm surge 5.6+ m, widespread loss of roofs, some buildings destroyed, all trees blown down

(a wind speed of 100 knots = 185.2 km per hour = 51.4 metres per second)

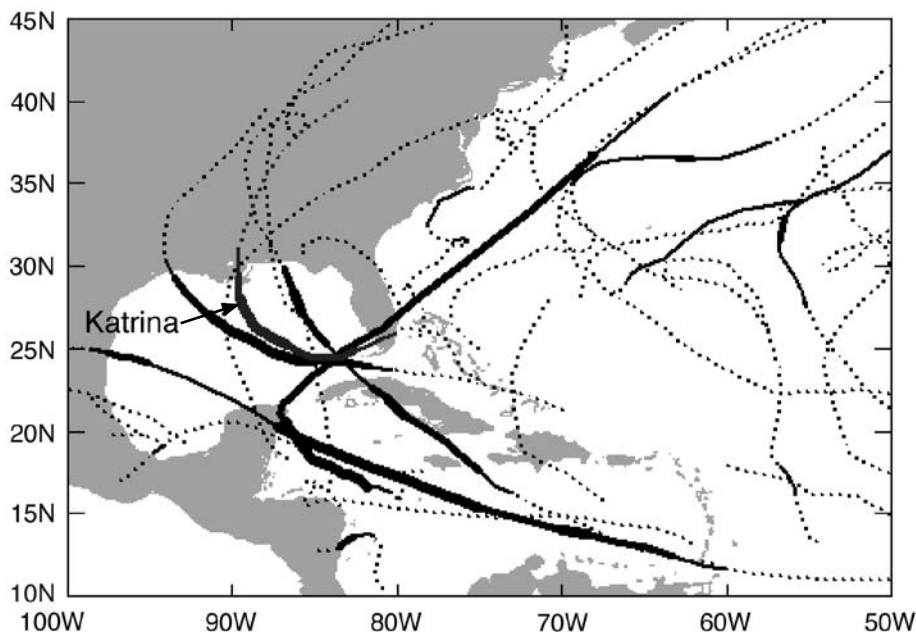
SO WHY WAS 2005 SO ACTIVE?

Several factors are involved. There was an extensive region across the equatorial Atlantic where the vertical wind shear (the change in wind speed with height) was unusually low. Vertical wind shear interferes with the vertical structure of a hurricane and inhibits hurricane formation. The rate of latent heat exchange (the transfer of water vapour energy from ocean to atmosphere) was 20% greater than the largest value in the previous 25-year period and, therefore, strongly favoured hurricane activity. Record warm surface temperatures across the Gulf of Mexico, Caribbean and tropical Atlantic provided the energy source to form and sustain hurricanes. Sea-level pressure was exceptionally low across the Caribbean, again aiding hurricane formation (5).

Many of these factors have been linked to climate-scale variabilities. Perhaps the most well-known of these is the El Niño-Southern Oscillation (ENSO); however, during 2005 conditions were ENSO neutral for most of the year. Other large-scale variabilities that have been linked to observed oceanic and atmospheric conditions include the Atlantic Multi-decadal Oscillation, the North Atlantic Oscillation and the Madden-Julian (40-day) Oscillation. It was the juxtaposition and magnitude of these causal factors that likely induced the record activity during the 2005 hurricane season. The effect of these was exacerbated by climate change, the largest contributor to the warm temperatures in the tropical Atlantic. Of the 0.9°C tropical Atlantic temperature anomaly (compared with a 1901-1970 baseline), 0.2°C was attributable to the weak 2004-05 El Niño; less than 0.1°C was attributable to the Atlantic Multi-decadal Oscillation; and most of the anomaly (0.45°C) was attributable to climate change (6).

A side-note to the extreme nature of the 2005 season is that none of the named storms traversed Puerto Rico and the Lesser Antilles (Windward and Leeward Islands). Despite the

very warm ocean surface temperatures, each of the Atlantic hurricanes passed around this region. While this absence of storm activity saved the island communities from the potential devastation of hurricane landfall, it also removed the ameliorating effects that tropical storms have for tropical regions.



This figure illustrates the named storm tracks (including hurricanes) for 2005. Dotted lines show paths of tropical storms; hurricane strength is shown by the thickness of the solid lines (3 groups: categories 1; 2 & 3 together, 4 & 5 together). The marked track is of Hurricane Katrina whose storm surge devastated New Orleans. Note the clear region centred around 65°W:20°N; no hurricanes passed over the very warm waters, which resulted in massive coral bleaching in the Lesser Antilles . Compare this ‘hole’ with the NOAA thermal stress images on the front cover and on pages 9-11.

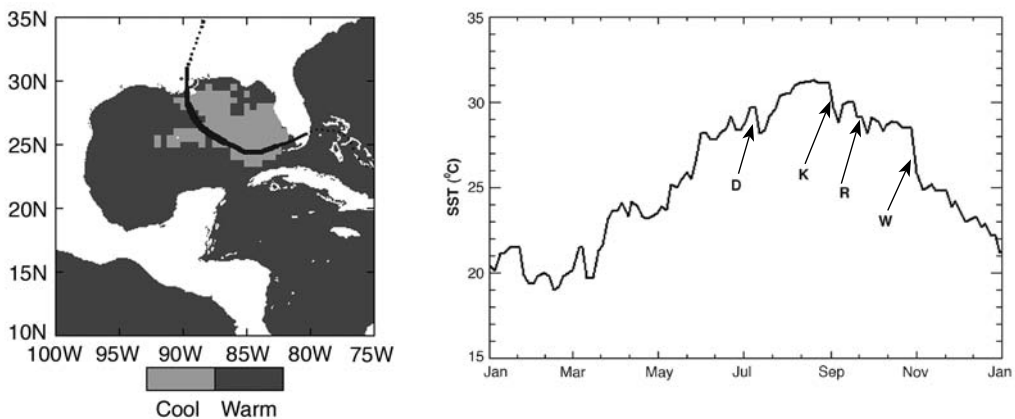
THE GOOD AND THE EVIL OF HURRICANES FOR CORAL REEFS

While there is often a perspective that hurricanes are only destructive and disastrous events, they also provide ecological benefits to tropical and sub-tropical environments. Rainfall gives a boost to wetlands and flushes out lagoons, removing waste and weeds. Hurricane winds and waves move sediment from bays into marsh areas, revitalising nutrient supplies. While there is always the potential for mechanical damage, coral reefs can also receive benefit from hurricanes during the warm summer months (1).

During the summer hurricane season, as ocean surface waters become warmer, corals often experience thermal stress. Hurricanes can alleviate this thermal stress by three mechanisms. First, as hurricanes absorb energy from surface waters through the transfer of latent heat, the temperature of the water is reduced (evaporative cooling). The magnitude of the cooling is related to the intensity and extent of the hurricane. Second, hurricanes also reduce sea surface

temperatures (SST) by inducing local upwelling, bringing deeper, cooler water to the surface. The amount of surface cooling resulting from these mixing mechanisms will depend on the hurricane wind speed and how the water temperature varies with depth at each location. Finally, the clouds of a hurricane shade the ocean surface from solar heating allowing the water to cool and reducing light stress.

The figure on the left shows regions of positive and negative sea surface temperature anomaly with the track of Hurricane Katrina over the cool wake. The graph on the right is a SST time-series at Sombrero Reef, Florida Keys showing the rapid drop in temperature following the passage of hurricanes Dennis (D), Katrina (K), Rita (R) and Wilma (W). Hurricane Katrina passed over the Florida Keys as a Category 1 hurricane on 26 Aug 2005, during the hottest period, reducing the temperature



stress and halting a temperature trajectory towards coral bleaching.

While larger, more intense hurricanes provide the greatest cooling near the ocean surface, they are also the most destructive. Waves and water movement significantly influence the structure and distribution of coral assemblages. Generally, the more delicate 'branching' corals (e.g. *Acropora* spp.) are more vulnerable to wave damage than corals with a 'massive' or 'boulder-like' growth form (e.g. *Porites* spp.). As a consequence, massive corals tend to dominate coral communities in areas regularly exposed to oceanic swells, while delicate species thrive in low energy areas such as lagoons and back-reef areas (2.). In addition, waves and tidal water movements scour some areas exposing the solid limestone structure of the reef, which provides a firm foundation on which corals can settle and grow. In other areas, water movement results in the accumulation of sediment and rubble, which is unstable and, therefore, less suitable for coral settlement.

The waves generated by hurricanes are larger and more powerful than those experienced under normal conditions and can affect all parts of a reef. As a consequence, they are the primary cause of hurricane-related damage to corals and coral reefs, often breaking coral branches and overturning colonies. Dislodged coral pieces can cause further damage as they are propelled onto other parts of the reef. In 2005, Hurricane Rita damaged the deep reefs of the Flower Garden Banks, while Wilma scoured the reefs of the Florida Keys.

Recovery from hurricane damage is variable. Often, branching corals recover quickly because of their rapid growth, and broken branches can even begin to regrow in new areas. However, recovery can be hindered by the accumulation and movement of coral rubble generated by the hurricane, and by increases in the abundance of algae, which compete for space within the reef. Terrestrial runoff resulting from heavy rainfall can also influence the nearshore reef ecosystems, smothering corals with sediment and other debris, as well as increasing nutrients (including those in fertilisers) that influence growth rates of algae, and lowering salinity, which can stress corals.

CONCLUSIONS

The influence of hurricanes on coral reefs can be beneficial and detrimental. Small hurricanes can provide fast relief during periods of thermal stress, whereas waves from large hurricanes can reduce a reef to rubble. Coral reefs have experienced these effects of hurricanes and survived for millions of years; however, in light of the rapidly changing climate, the ability of corals to recover from severe storms, while facing the combined effects of increasing thermal stress and ocean acidification, could be extinguished.

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4. THE 2005 BLEACHING EVENT: CORAL-LIST LOG

JESSICA MORGAN, SCOTT HERON AND MARK EAKIN

Coral reef scientists and managers were fortunate to have an early warning system in place prior to the damaging events of 2005. This chapter is a log of events that occurred in the Caribbean during 2005 and is largely based on messages sent out, and submissions to, Coral-List.

CORAL LIST

'Coral-List' is a coral reef information and news email forum maintained by NOAA's Coral Health and Monitoring Program, for coral reef researchers and managers throughout the world. Since 1995, the list has broadcast announcements and discussions of various local, regional, and global topics concerning coral reefs, including coral bleaching, disease and spawning, environmental monitoring, and upcoming meetings. Coral-List currently has more than 4400 subscribers. To register go to <http://coral.aoml.noaa.gov/mailman/listinfo/coral-list/>.

17-Mar-05 Coral bleaching reported on 2 reefs in Southern Bahia, Brazil (Itacolomis and Abrolhos); but the temperature rise is only 0.75°C above the maximum summer average. NOAA has not detected a major HotSpot in the satellite images; maybe this is a doldrum-like event.

16-May-05 First bad news: The U.S. National Hurricane Center has predicted a 70% chance of an above-normal Atlantic hurricane season. The outlook is for 12-15 tropical storms, of which 3-5 will become major hurricanes. This could be serious for reefs in the Caribbean. Bad hurricane years are often bad bleaching years as well.

26-May-05 Satellite images show potential coral bleaching and 'HotSpots' are appearing across the Caribbean earlier than usual. Winds are generally low and a pool of unusually warm water has formed northeast of the Lesser Antilles. NOAA Coral Reef Watch has sent out an email message calling for people to start checking for coral bleaching.

THERMAL STRESS AND HOTSPOTS

NOAA Coral Reef Watch uses satellite sea surface temperature (SST) data to produce twice-weekly global estimates of thermal stress on corals (<http://coralreefwatch.noaa.gov>). Thermal stress depends on the capacity of corals in different locations to tolerate heat; corals near the equator are comfortable in temperatures that would be stressful for corals that are used to cooler waters.

Because stress thresholds are location-specific, the expected temperature for a normal summer is determined for each location. To measure the stress level, the current SST is compared with this normal summer temperature. The difference between these indicates the current level of stress experienced by corals and is called the 'HotSpot.'

Coral bleaching HotSpot maps illustrate the magnitude and distribution of HotSpots using different colors that correspond to the number of degrees by which the SST exceeds the normal summer temperature. Examples of the maps are on pages 8 to 11

31-May-05 Reports are coming in from Colombia that they are seeing the highest sea surface temperature (SST) over the reefs so far this year, 29.9°C. Thankfully, there is no bleaching there ... (yet).

02-Jun-05 The trade winds have begun again, mixing and cooling the waters. While this has provided some relief, there are still concerns about coral bleaching – and we're only at the start of June!

16-Jun-05 The first Coral-List report of bleached corals for the Caribbean has come from the northwest coast of Colombia at Islas del Rosario, following sustained high water temperatures.

25-Jun-05 SSTs at Culebra, Puerto Rico, have reached 30.5°C and corals are bleaching. In some areas, 50% of corals have died. On top of this, there have been outbreaks of white plague-like syndrome and black band disease. The warmest temperatures here aren't usually reached until September and October.

05-Jul-05 SSTs have started to cool on the Caribbean coast of Panama but the accumulated thermal stress shown by the coral bleaching Degree Heating Week (DHW) values are still high. Corals have bleached near Bocas del Toro; hopefully this cooling will allow them to recover.

Hurricane Dennis, 05 to 13 July 2005

Hurricane Dennis was unusually strong for a July hurricane, reaching Category 4 status. Dennis made landfall four times; in Grenada, twice in Cuba and finally in western Florida. Wind speed is used to indicate a hurricane's strength, from Category 1 (weakest) to Category 5 (strongest) on the Saffir-Simpson scale (see Hurricane Chapter).

DEGREE HEATING WEEKS

The satellite-based coral bleaching Degree Heating Week (DHW) is an accumulation of thermal stress experienced by corals within the previous 12 consecutive weeks. A DHW value of 4°C-weeks indicates that significant coral bleaching is likely; widespread coral bleaching and mortality have been associated with DHW values exceeding 8°C-weeks. For each location, DHW are calculated by adding any HotSpot values greater than 1°C and multiplying by the half-week time step of the NOAA Coral Reef Watch data. For example, if the HotSpot values for a particular location were [1.0, 2.0, 0.8, 1.2] the contribution to the DHW from these four half-week values would be $(1.0+2.0+1.2)*0.5 = 2.1$ °C-weeks. Note that 0.8 is not included in the calculation as it is less than 1°C. Examples of maps derived illustrating the distribution of DHW values can be seen on the first page inside the front cover; the front cover is a stylized version of this map.

13-Jul-05 NOAA Coral Reef Watch launches a new operational product: the Satellite Bleaching Alert system.

15-Jul-05 More reports of bleaching have come in, including extensive paling of corals around Abacos in the Bahamas. The HotSpot image on Executive Summary page 8 illustrates the developing HotSpot.

Hurricane Emily, 11 to 26 July 2005

Hurricane Emily eclipsed the record set by Dennis, just 6 days earlier, as the strongest recorded pre-August hurricane and is the only Atlantic hurricane to have reached Category 5 status before August. Emily inflicted damage on Grenada as a tropical storm before intensifying in the western Caribbean. Emily crossed the Yucatan Peninsula (Category 4) and again made landfall in northern Mexico (Category 3).

26-Jul-05 Amazing! In the first two weeks of the Satellite Bleaching Alerts (SBA) system, emails have been sent for all 6 Caribbean/Atlantic sites. The U.S. Virgin Islands have thankfully dropped back to a condition of no thermal stress; Puerto Rico, the Bahamas, and Bermuda have gone up to Bleaching Watch, while Belize has dropped down to Bleaching Watch. There is some concern for the Florida Keys; there is a Bleaching Warning there at the moment.

02-Aug-05 Things have become worse; the National Hurricane Center has upgraded the probability of an above-normal hurricane season to 95-100%. The prediction is now for 18-21 tropical storms, including 5-7 major hurricanes.

05-Aug-05 Corals have become pale and bleached in Bermuda where calm seas and clear skies are persisting and there have been reports of unusually large numbers of nudibranchs (a type of sea slug). Reports of sponge diseases have increased in Cozumel, Mexico; requests have gone out for more sightings. It is worse around St. Croix in the U.S. Virgin Islands where sponges appear to be absent - should we send out a search party?

08-Aug-05 Elkhorn corals (*Acropora palmata*) in Biscayne Bay have lost tissue following the passage of Hurricane Dennis through the Florida Keys. With the prediction of more hurricanes, will more corals lose tissue?

SATELLITE BLEACHING ALERTS

Satellite Bleaching Alerts (SBA) notify reef managers when changes occur in the environmental conditions relevant to coral bleaching at or near their reef. NOAA Coral Reef Watch transmits emails for 24 locations around the world, including 6 strategic reef sites across the greater Caribbean region. SBAs are sent to registered users whenever HotSpot and Degree Heating Week indicators show that the thermal stress level has passed a critical threshold; either increasing or abating. Subscription is free at <http://coralreefwatch-satops.noaa.gov/SBA.html>; additional SBA sites are under development and further locations can be requested.

Bleaching Watch: Keep an eye out! Corals are experiencing low-level thermal stress. Temperatures have exceeded the usual summer maximum but have not yet reached the Bleaching Threshold. Degree Heating Weeks (DHWs) are not yet accumulating.

Bleaching Warning: Get prepared now. The HotSpot is now at least 1°C and corals are stressed. DHWs have begun to accumulate and are at 1°C-week.

Alert Level 1: Corals are probably bleaching or will soon! DHWs have reached 4°C-weeks, signifying that thermal stress has reached levels that cause bleaching. Generally, corals will respond to this level of thermal stress in the next 1-3 weeks, depending on the species and other local factors.

Alert Level 2: Double trouble. At DHW of 8°C-weeks, thermal stress is widespread and you can expect to see mass coral bleaching. Unfortunately, by this time, the thermal stress has persisted long enough that some corals will probably die soon.

No Stress: Temperatures have cooled and hopefully stressed corals will recover. At least they are no longer under thermal stress.

18-Aug-05 Extensive bleaching has been seen in the Florida Keys, right after an SBA Alert Level 1 email was sent on 13 August. SST has been around 31°C, with calm and sunny conditions. There could be more trouble in store for Florida's reefs; a strong HotSpot is developing, as shown in the image on page 9.

23-Aug-05 More bleaching has been seen in Biscayne Bay, Florida Keys, and now corals near Palominitos Island, Puerto Rico are bleaching.

Hurricane Katrina, 23 to 30 August 2005

Hurricane Katrina was one of the most devastating natural disasters in the United States history. Katrina was the most costly hurricane to strike the U.S., making landfall in Florida (Category 1) and then intensifying to Category 5 over the Gulf of Mexico before striking Louisiana/Mississippi (Category 3). Katrina was exceptionally large with hurricane-force winds extending 170 km from the centre and storm-force winds out to 370 km. The 8 m storm surge that accompanied Katrina caused major flooding in New Orleans and along the northern Gulf coast. However, Katrina also did some good in the Florida Keys, as a Category 1 hurricane, mixing up the waters and cooling overheated reefs.

27-Aug-05 Record-breaking thermal stress is affecting Sombrero Key in the Florida Keys and an SBA Alert Level 2 has been issued. Hurricane Katrina is crossing over South Florida – are we going from bad to worse?

29-Aug-05 According to an article in the Key West Citizen, Hurricane Katrina has really helped the Florida Keys, providing much-needed relief from thermal stress.

01-Sep-05 Several coral species are bleaching on the reefs of Belize, ranging in intensity from paling to bright white.

06-Sep-05 SST has dropped by more than 2°C at Sombrero Key from a week ago. The SBA level has been reduced to Bleaching Watch; hopefully these corals can recover from the thermal stress. The HotSpots are now covering extensive areas of the Caribbean, as seen on the image on page 10.

09-Sep-05 Hard corals in eastern Puerto Rico have bleached extensively, and octocorals, gorgonians, and zoanthids have also bleached. Water temperatures are around 29.5-30°C and there is barely any wind.

12-Sep-05 Things are looking bad. Corals in Biscayne Bay range from unbleached, to pale, to extensively bleached, and black band disease has been observed. The Florida Keys corals range from slight to severely bleached, and divers have reported recently-dead Elkhorn coral. Corals in southwestern Puerto Rico have started to bleach and white plague has also been seen.

14-Sep-05 The first bleaching of the flower coral *Mussa angulosa* has been recorded in northeastern Puerto Rico, as well as bleaching and mortality reports of *Palythoa caribbaeorum*. Bleaching has also been seen in northern and western Barbados and southeastern Costa Rica.

15-Sep-05 A report has come from eastern Puerto Rico of the first-ever record of a bleached colony of Elkhorn coral in the region. There has been extensive bleaching and mortality, as well as an outbreak of black band disease. Scientists have noted that for some reason there does not appear to be any cleaning gobies on the reefs - are the gobies stressed too?

17-Sep-05 Now coral bleaching has been seen in the British Virgin Islands. Are any reef areas safe?

19-Sep-05 Not only are hard corals, octocorals and zoanthids bleaching around Barbados, scientists have noted unusually high mortality of moray eels and white sea eggs (a type of sea urchin).

21-Sep-05 Thermal stress has progressed southward and eastward through Cuba, Puerto Rico and the Virgin Islands. DHW levels have exceeded 8°C-weeks, so the likelihood of coral mortality is high. It's hard to not feel helpless.

Hurricane Rita, 18 to 26 September 2005

Hurricane Rita took only 36 hours to strengthen from a tropical storm to a Category 5 hurricane as it passed across the central Gulf of Mexico, making it the most intense hurricane ever recorded in the Gulf; breaking the record set by Katrina just weeks earlier. While intensifying, Rita passed near Florida Keys (as Category 2), mixing the waters that had begun to warm again following the cooling by Hurricane Katrina. Rita struck the Texas-Louisiana border as a Category 3 hurricane and completely destroyed some coastal communities.

24-Sep-05 Is there a weather conspiracy against corals? There is an extended area of low pressure over the northeastern Caribbean that means light winds for the next two weeks. The northern Jamaican coast has experienced low-level bleaching, but the southern coast has areas where 80% of the corals are bleached. There is good news, with little-to-no bleaching in Bonaire and Curaçao and mass coral spawning has occurred in Curaçao as usual.

26-Sep-05 It has been the hottest August and September in 15 years of ocean temperature monitoring at St. John, U.S. Virgin Islands! Temperatures at 16 m depth have exceeded 30°C since 5 September and just peaked at 30.8°C. Most coral species are severely bleached.

30-Sep-05 The Association of Marine Laboratories of the Caribbean has called for the establishment of a long-term monitoring program for biological communities and physical environment conditions on reefs. Hopefully that will help us learn how to help corals survive through events like this.

05-Oct-05 Devastating news; a report has been received that more than 90% of corals down to 30 m are bleached in the British Virgin Islands. Bleaching has also been seen along the northern coast of Puerto Rico. DHW values have reached record highs in these areas. There is a sense of helplessness in our offices; apparently all we can do is issue more threatening reports. The image on page 11 shows the maximum extent of HotSpots across the Caribbean.

08-Oct-05 An SBA Alert Level 2 has been issued for the U.S. Virgin Islands and DHWs in the region now exceed 12°C-weeks. At least 90% of corals along the northern shore of St. Croix are white or paled. Thankfully, the sun has now moved south, so things should begin cooling off (we hope!)

11-Oct-05 DHW values have continued to escalate in the eastern Caribbean; when will it stop? Predicted cloud and rain should bring relief from thermal stress for those regions lucky enough to get them.

13-Oct-05 The Caribbean coast of Tobago has experienced its worst recorded mass coral bleaching, with around 80% of corals affected by the 31°C conditions. Near St. Croix, U.S. Virgin Islands, 50-75% of hard corals and several soft coral species have bleached.

19-Oct-05 Observations in the Flower Garden Banks National Marine Sanctuary (NMS) have shown significant mechanical damage from the passage of Hurricane Katrina. Coral boulders larger than 2 m were rolled over! In addition, at least one-third of colonies have bleached.

22-Oct-05 Temperatures are in excess of 29°C down to 20 m at Guana Key in the Bahamas and bleaching has affected 96% of *Montastraea* colonies and 50% of *Porites* colonies.

23-Oct-05 Batten down the hatches! Coral-List has to be temporarily shutdown because of the imminent arrival of Hurricane Wilma and anticipated power outages.

Hurricane Wilma, 15 to 25 October 2005

Hurricane Wilma was the most intense Atlantic basin hurricane on record, with a lowest central pressure of 882 hPa. Wilma wreaked havoc on the Yucatan Peninsula (Category 4), sitting over Cozumel for more than 36 hours, before causing extensive damage in Florida (Category 3).

25-Oct-05 Above-normal temperatures have continued across the Caribbean. The centre of the heat stress has moved south along the Lesser Antilles and NOAA reports intensified bleaching in many areas (DHW>12°C-weeks). Bonaire and Curaçao are now seeing bleaching stress (DHW>4). Major newspapers, *the Washington Post* and *Los Angeles Times*, have reported the bleaching caused by temperature stress across the Caribbean.

27-Oct-05 Reef Check has called for the mobilization of its teams throughout the Caribbean for bleaching and post-bleaching surveys. Corals along the northern coasts of Colombia and Venezuela (20% of colonies) have bleached; in the Flower Garden Banks NMS, around 40% of colonies have bleached.

01-Nov-05 Scientists in Mexico are assessing the damage to corals from Hurricane Wilma. In the Lesser Antilles, the centre of the heat stress has expanded southward and has affected even more coral regions.

02-Nov-05 The International Coral Reef Initiative has passed a Statement of Concern encouraging countries in the region to take immediate action to document the extent of bleaching, mortality, and recovery; and to target surviving coral reefs for protection.

04-Nov-05 Good and bad: corals have started to recover their color over the past 10-14 days in the U.S. Virgin Islands and Puerto Rico. Many Elkhorn and Staghorn (*Acropora palmata* and *A. cervicornis*) corals have been killed during the thermal event and disease outbreaks and lesions have hit bleaching-affected corals.

Coral disease appears to be spreading! Outbreaks of coral disease have been linked to periods of thermal stress. As such, the prevalence of disease often increases following bleaching events, as already stressed corals are more susceptible to infections. As temperatures return below stressful levels, disease progression frequently slows.

07-Nov-05 The U.S. Coral Reef Task Force has passed a resolution for its members to lead a coordinated interagency response to monitor the ecological and sociological impacts of the Caribbean bleaching; already one of the worst regional-scale events on record. The resolution also called for improved forecasting of thermal stress and its impacts on coral reef ecosystems.

11-Nov-05 In northern Colombia, bleaching ranges from partial to severe across several species, with water temperatures at 29°C. At Cayo Sombrero, Venezuela, the whiteness of corals has generally increased.

22-Nov-05 The SBA alert level for the U.S. Virgin Islands and Puerto Rico has been reduced to No Stress. It seems the bleaching here is finally over. The big question is whether the corals can recover.

28-Nov-05 Is this a case of ‘hit them while they’re down’? Outbreaks of white plague have been recorded in a variety of species in both the U.S. Virgin Islands and the southwest of Puerto Rico. The outbreaks are most intense in offshore waters where the depth is 15 m or more. Though the progress of the disease has slowed as temperatures have dropped, some coral deaths have been attributed to the disease. Black band disease has been seen in the British Virgin Islands.

01-Dec-05 The 2005 Hurricane season officially ended, with a record 26 named storms, including a record 13 hurricanes (5 of which were severe). This was the first time in history that the seasonal list of names was exhausted and the back-up Greek letter system had to be used.

16-Dec-05 Mixed reports; no sightings of bleaching in Bermuda; some totally bleached colonies at Grand Cayman Island but no mortality. At La Parguera, Puerto Rico, while most corals have begun to recover their color, some remain completely white and there has been high mortality among Elkhorn, Staghorn and *Millepora* corals.

21-Dec-05 Most nearshore corals in Colombia are dead, while corals 100 m offshore have experienced outbreaks of various diseases.

30-Dec-05 Tropical Storm Zeta has formed, missing the record of the latest ever to form by 6 hours. It finally dissipated on 6 January 2006.

03-Jan-06 Bleaching in the Flower Garden Banks NMS is down to 10% of colonies; however, white plague symptoms have been observed in more than 2%.

31-Jan-06 Coral mortality levels in Martinique have hit 18%. The mortality is likely to be the result of an outbreak of white plague.

03-Mar-06 One up, one down. Bleaching now only affects 5% of colonies in the Flower Garden Banks NMS, but the incidence of white plague has risen to around 7%, with up to 20% of colonies infected in localized areas.

08-May-06 Are Caribbean reefs disappearing? Elkhorn (*Acropora palmata*) and Staghorn (*A. cervicornis*) corals will be listed as threatened species under the U.S. Endangered Species Act. This is the first time any coral species have been officially classed as endangered. Let’s hope we don’t see another year like this anytime soon.

16-Oct-06 Corals at some locations are still bleached. Most researchers have ended monitoring of mortality from 2005, as it has become too difficult to distinguish damage from the 2005 warming from later stress.

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5. STATUS OF THE MESOAMERICAN REEF AFTER THE 2005 CORAL BLEACHING EVENT

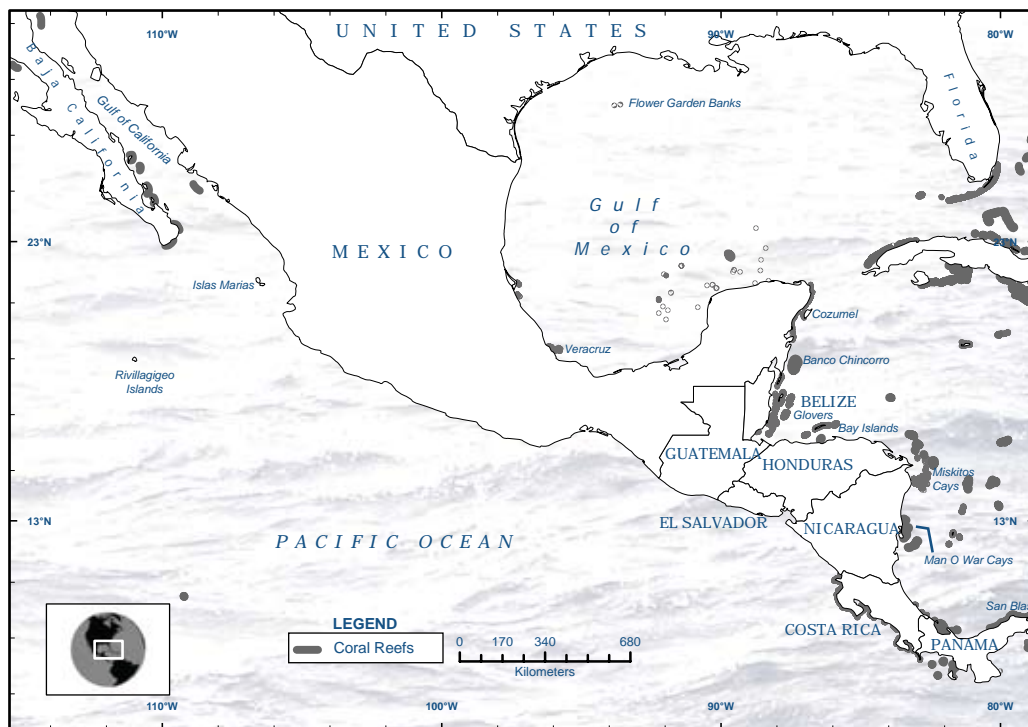
MELANIE McFIELD, NADIA BOOD, ANA FONSECA, ALEJANDRO ARRIVILLAGA,
ALBERT FRANQUESA RINOS AND ROSA MARÍA LORETO VIRUEL

SUMMARY

- Mass bleaching events in 1995, 1998 and 2005 have affected the reefs in the Mesoamerican Reef (MAR), although the 2005 bleaching resulted in little to no coral mortality;
- The 1995 event caused widespread bleaching, but minimal mortality (~10% of colonies had partial mortality in Belize);
- 1998 was the most significant bleaching event for the MAR, combined with a catastrophic hurricane that culminated in about 50% reduction in coral cover in Belize, with somewhat less in the other countries;
- Large-scale bleaching in late 2005 affected most reefs within the MAR, however, coral mortality was lower than in previous years;
- The active 2005 storm season may have contributed to greater mixing of oceanic waters and minimized 'doldrum conditions' that were associated with the previous, more severe bleaching events in the MAR;
- Reefs in Mexico were damaged by Hurricanes Wilma and Emily, but most of the other 2005 storms passed through the Yucatan channel into the Gulf of Mexico without causing substantial damage to reefs;
- The devastating coral bleaching and hurricanes of 1998 initiated the planning for potential adaptation and mitigation strategies into reef management efforts;
- The bleaching and hurricanes in 2005 may have further delayed potential recovery from the bleaching-related losses in 1995 and 1998; and
- Coral cover throughout the region remains moderately low, with little to no overall recovery from the 1998 losses.

INTRODUCTION

The 1000 km long Mesoamerican reef system (MAR) is recognized as a global conservation priority owing to its biodiversity, cultural and socioeconomic values. The Caribbean coast and cayes of Mexico, Belize, Guatemala, and Honduras contain an abundance of diverse and productive ecosystems including coral reefs, seagrass beds and mangrove forests that provide critical habitats for commercial fish stocks and many threatened species. However, the ecological integrity of the MAR continues to be threatened by various anthropogenic and natural factors, ranging from pollution, tourism and unsustainable fishing activities to recent global climate change.



Map of Mesoamerican Reef Ecoregion

Bleaching and storm damage in the MAR is similar to what has happened in most reef regions of the world. This has changed the regulatory and management perspective, because large-scale coral bleaching events are beyond a local manager’s capacity to control. Identifying practical and effective management responses for MAR has proven very difficult; current efforts are focused on restoring and maintaining reef ecosystem resilience.

Since the first mass bleaching in 1995, the MAR has suffered similar widespread bleaching events in 1998 and 2005. Although the 1995 mass bleaching event caused some coral mortality, the damage from the 1998 bleaching, combined with damage from 1998 Hurricane Mitch, was far more severe, resulting in a 50% average decline in live coral cover. In 2005, six sites in Belize were re-surveyed with the same methods, and no signs of recovery were found. There was no comprehensive assessment of reef recovery (or not) throughout the MAR region prior to the 2005 bleaching event. The limited data that are available suggest there had been little change from 1999 to 2005.

THE 2005 BLEACHING EVENT

The coral bleaching events of 1995, 1998 and 2005 coincided with unusually high sea surface temperatures and calm seas (although fewer data are available on wind speeds). The period between July and November, 2005 was the warmest for the Caribbean in 100 years; however MAR reefs were less damaged in 2005 than many other reefs in the wider Caribbean. Coral bleaching within the MAR was first observed in mid-July, and apparently peaked in late October to early November, with up to 40% of corals being affected.

The Mesoamerican reef will likely continue to be affected by future bleaching events as sea temperatures are predicted to increase. However, environmental and intrinsic characteristics of each reef may alter the extent of resulting coral mortality or other impacts on reef resilience. The amount of heat stress on a specific reef is highly variable and can be influenced by local environmental factors (e.g. currents, wave exposure, and light penetration). Intrinsic factors, such as genetic make-up or heat resistance of symbiotic zooxanthellae, can also alter the heat-tolerance of different coral species or reefs. These inherent resiliency factors will also have a strong influence on which reefs are likely to survive into the future. Reef managers will need to apply precautionary management principles to control other stressors on the reefs, such as dredging operations, mangrove clearance and high density coastal developments. Mass bleaching has highlighted the critical need to integrate these stresses into management efforts.

REEF CHECK MONITORING IN THE CARIBBEAN

As threats to reefs continue to grow, Reef Check's community-based monitoring program is becoming increasingly important to document the status of the world's coral reefs. Hurricanes, El Niño events, disease outbreaks, bleaching and other stresses caused by human activities have increased coral mortality throughout the world in the past 25 years. Coral bleaching brought about by abnormal increases in sea temperatures is now considered the greatest threat to coral reefs. The most severe bleaching event to date occurred in 1998 and affected the entire Indo-West Pacific region. Subsequent coral mortality often reached 50% and, in some places, more than 90% of the hard corals were killed. The Caribbean region was also affected in 1998, but average mortality generally ranged between 5-10%. During 2005, another massive bleaching event occurred as sea temperatures in the Caribbean matched or even surpassed those recorded in 1998.

Reef Check teams conducted more than 185 benthic surveys in 16 countries throughout the Caribbean between January 2005 and June 2006 to determine the extent of coral bleaching and subsequent mortality at local to regional scales. On a Caribbean-wide scale, the percent cover of bleached coral ranged between 2% and 62%, and bleaching-related mortality ranged between 0% and 27%. There was little difference in the extent of bleaching between shallow and deep reefs and the average percent cover of live hard coral did not change significantly as a result of coral bleaching.

Substantial coral bleaching was recorded in Belize, Jamaica, St. Lucia and the British Virgin Islands. In Belize, St. Lucia and the British Virgin Islands, there was little subsequent mortality and no reduction in coral cover. In Jamaica, a large proportion of the corals that bleached subsequently died, but because the coral cover was generally low, the mortality did not reduce the coral cover significantly (see p 79).

If the 1998 and 2005 large-scale bleaching events are representative of a general pattern, then abnormally high sea temperatures within the Caribbean seem to cause extensive bleaching but little subsequent mortality. This is possibly a result of the recent domination of massive corals, which are more resilient than branching corals, within Caribbean coral communities, and/or because Caribbean corals are frequently exposed to larger fluctuations in sea temperature, allowing them to better adapt.

With greater investments in a strengthened monitoring network, the standardized survey methods employed by Reef Check enable the size of impacts resulting from large-scale environmental stresses, such as El Niño and climate change, to be quantified at local to global scales. Data resulting from large-scale standardized surveys are increasingly important in tracking reef responses to impacts from a variety of sources and are an extremely useful tool for coral reef management and conservation (from Cori Kane, ckane@reefcheck.org and Gregor Hodgson, gregorh@reefcheck.org).

Summary of results of Reef Check surveys conducted during the 2005 bleaching event and in the following months to June 2006, to determine the percentage cover of bleached coral and levels of subsequent mortality on coral reefs throughout the Wider Caribbean (- indicates no data).

Country	Mean % Bleaching	Mean % Mortality
Bahamas	16.8	-
Belize	27.9	6.5
Brazil	5.7	-
British Virgin Islands	55.0	2.1
Colombia	1.0	-
Dominica	4.6	0
Dominican Republic	26.8	-
Honduras	-	14.4
Jamaica	33.7	12.5
Mexico	25.2	8.5
Netherlands Antilles	-	4.2
St Lucia	43.8	4.3
St Vincent	75.0	-
US Virgin Islands	100	34.3

Belize

The longest continuous barrier reef system in the western hemisphere extends approximately 260 km along the Belize coast, and along with the diverse assemblage of lagoonal patch reefs, fringing reefs, faroes and offshore atolls, covers about 1400 km². The reefs were once considered to be amongst the most flourishing reefs of the Caribbean, although now the current status is generally comparable with the rest of the Caribbean.

Status of coral reefs prior to 2005: The combination of disturbance events and chronic stresses has caused a decline in live coral cover and parallel increases in macroalgae on many reefs. The *Acropora* species have suffered a dramatic reduction in live cover since the late 1970s as a result of white band disease, and the region-wide die-off of the long-spined sea urchin grazer (*Diadema antillarum*). In 1998, the most severe coral bleaching event on record occurred, along with the catastrophic impacts of Hurricane Mitch that produced torrential rains, flooding, and destructive waves that caused considerable mechanical damage to reefs. The combination of bleaching, hurricane damage, and increasing chronic local stresses, has resulted in dramatic reductions in coral cover: 62% in southern Belize; 55% in the north; 45% on the atolls; and 36% on central reefs.

Long-term data exist for a few sites in Belize; live coral cover on shallow patch reefs in Glovers Reef atoll has decreased from 80% in 1971, to 20% in 1996, and to 13% in 1999. The inner fore-reef region at Carrie Bow Caye had 30-35% coral cover in the 1970s, but declined to 12-21% in 1995. Similarly on the fore-reef at Channel Caye (3-15 m depth), an inner-shelf faroe, live coral declined from 85% in 1986 to 60% in 1996, primarily because of disease and loss of staghorn corals (*Acropora cervicornis*), with partial replacement by thin leaf lettuce coral (*Agaricia tenuifolia*). Subsequently, bleaching in 1998 devastated this reef, reducing coral cover to about 5% in 1999. In 1992, the coral cover on the barrier reef off Ambergris Caye and Gallows Reef (near Belize City) was 25% and 20% respectively. In 1993, the coral cover on the shallow Mexico Rocks patch reef off Ambergris Caye was 84%, but dropped to 66% in 1995 primarily as a result of the 1995 coral bleaching event. Prior to 1998, most impacts on reefs in Belize were from diseases and hurricanes, although regional increases in nutrient concentrations and sedimentation, loss of *Diadema*, moderate over-fishing, and bleaching were also likely contributors. The combined impacts of mass coral bleaching and Hurricane Mitch in 1998 exacerbated the rate of reef decline.

Major anthropogenic threats to Belize's reefs include coastal habitat alteration (mangrove clearance, dredging operations), sedimentation, agrochemical and domestic pollution (mainly associated with coastal development, and inadequate solid and liquid waste disposal), over-fishing, and direct impacts from tourists, boat anchors and groundings. The tourism industry is growing rapidly, providing the impetus for many of these growing pressures. Significant conservation efforts have been underway for over two decades to develop a system of marine protected areas (MPAs) to foster reef protection.

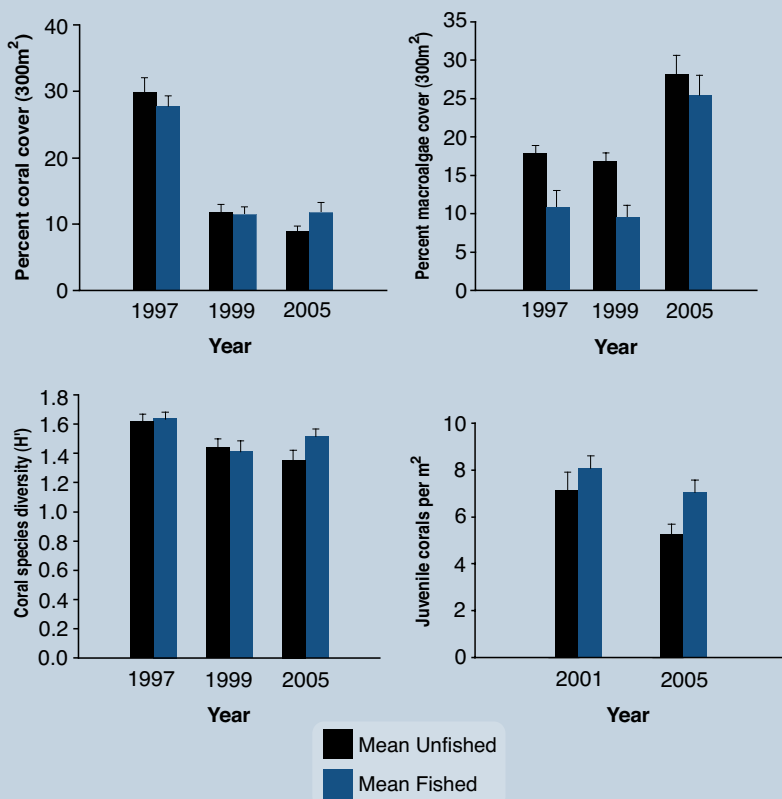
Effects of the 2005 Bleaching Event: The bleaching events in 1995 and 1998 caused some (mostly partial) coral mortality on most reefs in Belize. Sea surface temperatures (SSTs) surpassed the average summer maximum in both years beginning in late September in 1995 and early September in 1998. The bleaching event of 2005, while devastating to parts of the Eastern Caribbean, was less severe in Belize than the 1995 or 1998 events. No coral mortality in

ASSESSING RECOVERY OF REEFS IN BELIZE

The recovery of Belize’s reefs from the combined impacts of mass bleaching and Hurricane Mitch in 1998 were investigated in early 2005 to determine whether no-take protection status could accelerate potential recovery (i.e. increase resilience as defined by 4 indices: the abundance/diversity of benthic functional groups; hard coral diversity; coral recruitment; and herbivore abundance). Data were collected in 2005 at 3 highly protected sites and 3 reference sites and compared with data collected prior to or immediately after the 1998 event. There has been little recovery since 1998, with live coral cover at the 6 sites remaining less than 15%.

Because of the high level protection, it was predicted that the no-take reefs would exhibit significantly greater live coral cover and juvenile coral densities, and lower macroalgal cover than the fished reefs. However, there was no significant difference in mean live coral cover and coral diversity between fished and no-take reefs. Moreover, the density of juvenile corals was greater on fished reefs and the cover of macroalgae was significantly greater on unfished reefs.

From: Nadia Bood (nbood@wwfca.org), Melanie McField (mcfield@healthyreefs.org) and Rich Aronson (raronson@disl.org).



Belize was attributed to this 2005 bleaching event, possibly because of the relatively late onset, the cooling effects of numerous tropical storms and hurricanes, and possibly because many of the corals susceptible to bleaching had died during earlier events. Despite the lack of apparent bleaching related mortality in 2005, coral bleaching remains the major threat to all reefs in Belize; including the most remote and most well-protected (in terms of MPA management). While all nearshore and some offshore reefs are threatened by a variety of chronic local stresses, mass coral bleaching events threaten all reefs and may inhibit the natural ability of bleaching-damaged reefs to recover from repeated bleaching events.

Data from the Mesoamerican Barrier Reef System (MBRS) Project between early July and late September 2005 showed the first bleaching on the Belize reefs in mid July with 25% of colonies affected. The proportion of bleached colonies increased through August and September. Although no data are available for Belize after September, bleaching was observed in Belize (Turneffe, Ambergris Caye, Glovers Reef, among others) through to mid-November. Not all corals bleached and most that did were only partially bleached. Bleaching occurred primarily in colonies of *Siderastrea siderea*, *Montastraea* spp., *Diploria* spp. and *Agaricia* spp.

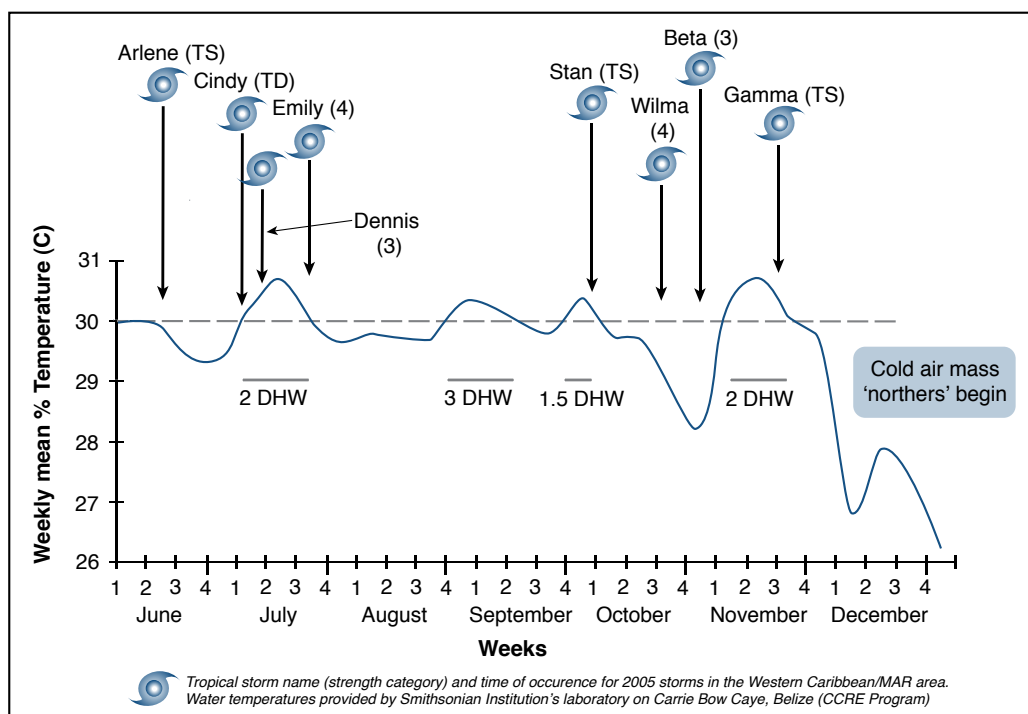
The extent of bleaching in Belize in 2005 is seen as the number of coral colonies affected in the Northern Summer. Data provided by MBRS Synoptic Monitoring Program (www.mbrs.org.bz)

Location	Month assessed (n = number of colonies)	Colonies Affected by Bleaching (%)
Belize	July (n = 488)	25
	August (n = 505)	19
	September (n = 221)	39

It may not be coincidental that 2005 was the most active storm season in the Western Atlantic in the past century. There were repetitive decreases in sea surface temperatures, which appear to coincide with the passage of intense storms that probably increased mixing and reduced SSTs. Thus, these storms may have contributed to the relatively low level of mortality of corals in Belize in 2005. A similar, but less dramatic, hurricane caused similar cooling during the 1995 bleaching event.

For four intervals between early July and mid November 2005, the average weekly SST in Belize exceeded the 30°C bleaching threshold for corals in the region, resulting in between 1.5 and 3 'Degree Heating Weeks' of temperature stress. On each occasion the stress was quickly reduced by rapid drops in temperature and coincident storm activity. By late November the regular cool winds, the 'northers', lowered sea temperatures.

Impacts of Hurricanes in 2005: Hurricanes have had a relatively regular impact on the reefs of Belize, but hurricanes Hattie (1961) and Mitch (1998) were exceptional. Hurricane Hattie reduced live coral cover on many reefs by 80%; however reefs subsequently recovered, at least to some extent. Hurricane Mitch in 1998 did not make landfall in Belize, but the pounding waves resulted in extensive physical damage throughout Belize, particularly on the Southern reefs. The heavy rainfall associated with this slow-moving storm also resulted in major flooding that damaged both inshore and offshore reefs of Belize and Honduras.



Water temperatures in 2005 reached the bleaching threshold (around 30°C) on several occasions, however the passage of tropical storms in the Gulf of Mexico and Western Caribbean between June and December may have contributed to the series of sharp temperature declines noted in the graph above.

The numerous tropical storms and hurricanes by-passing Belize in 2005 may have benefited the reefs of Belize by lowering SSTs, truncating the cumulative thermal stress, and thereby reducing the eventual extent of coral mortality.

Status of Reefs in 2006: A comprehensive reef assessment was conducted by WWF and partners in summer 2006 using the Atlantic and Gulf Rapid Reef Assessment (AGRRA) protocol. This survey found negligible bleaching and minimal recent mortality on 141 reefs that were selected based on geomorphology and a randomized design using the millennium coral reef maps for the region. Only 207 of the 5614 colonies assessed (3.7%) showed any signs of coral bleaching. Interestingly, bleaching incidence was higher among fore-reef sites compared with other reef habitats. Disease infestation was also low overall, with less than 2% of colonies affected by any disease. Mean recent mortality for the 140 reefs (5614 coral colonies) was less than 1.5%, with no significant differences among habitats. Although the 2005 bleaching event did not cause significant damage to Belize's reefs, overall live coral cover remains relatively low, averaging about 10% and the bleaching may have slowed recovery by 1 to 2 years.

Fore- and pinnacle reefs were dominated by colonies of *Agaricia*, while *Porites* dominated patch reefs and reef flats. Mean fleshy macroalgae cover was 16% on fore-reefs, 18% on patch reefs, 15% on reef flats and 14% on pinnacle reefs. Coral recruitment was greatest on pinnacle reefs (7 per m²) followed by reef flats (4/m²), patch reefs (3/m²) and fore-reefs (3/m²). Herbivorous

fish (parrotfish and surgeonfish) biomass was 2.7 kg/100m², 1.8 kg/100m², 1.6 kg/100m², and 1.3 kg/100m² on pinnacle reefs, fore-reefs, reef flats and patch reefs respectively.

A summary of reef status in Belize in 2006 shows that the 2005 bleaching event resulted in only low levels of prolonged coral bleaching, disease and mortality. Data provided by WWF.

Reef Habitat (n = number of colonies assessed)	Mean Coral Cover (%) (± S.D)	Colonies Affected by Bleaching (%)	Colonies Affected by Disease (%)	Recent Colony Mortality (%)
Fore-Reef (n = 2295)	11 (± 4.8)	5.7	1.6	0.9
Patch Reef (n = 1348)	11.5 (± 5)	1.9	1.3	2.1
Pinnacle Reef (n = 156)	15.2	1.9	0.6	0.6
Reef Flat (n = 1815)	11.3 (± 7.1)	2.7	1.3	1.0

Socioeconomic impacts and management responses: The lives of many Belizeans are inextricably linked to the health of their coral reefs through their dependence on the tourism and fishing industries, and their need for coastal protection (low-lying coastlines). For centuries, the reefs have provided cultural, ecological and economic benefits as well as physical protection during storms and hurricanes. Belize’s growing tourism industry accounts for about 23% of the GDP (based on 2002 figures) with a total annual value of US\$194 million. The fishing industry remains an important contributor with export earnings of US\$67.16 million in 2005 (3.8% of GDP in 2005). Based on Caribbean averages, the value of shoreline protection in Belize is roughly estimated at US\$35 to US\$100 million per annum. The estimated total value of goods and services provided is roughly US\$150 million per year (based on Belize’s proportion of Caribbean reefs as calculated by Reefs at Risk Caribbean). A full economic evaluation of Belize’s reefs will be conducted in 2007 by World Resources Institute (WRI) and WWF.

The reefs in Belize have declined during the last decade from a generally healthy condition to currently having lower coral and fish abundances than other areas of the Caribbean. There are now many marine conservation and monitoring programs in Belize, and 18 MPAs encompassing about 250,000 ha. Furthermore, the increased global significance of Belize and the wider Mesoamerican Reef is demonstrated by the establishment of regionally focused projects and initiatives, including: the Mesoamerican Barrier Reef System Project, a Global Environment Facility (GEF)/World Bank project that is now poised to enter its second 5-year phase; WWF’s Mesoamerican Reef Ecoregional Program; the Nature Conservancy’s Mesoamerican Reef Program; the Wildlife Conservation Society’s marine program in Belize; the International Coral Reef Action Network (ICRAN) Mesoamerican Reef Alliance; and the Healthy Mesoamerican Reef Ecosystem Initiative. Since late 2003, however, national reef management efforts in Belize have suffered from the loss of funding and capacity within the Belize Coastal Zone Management Authority and Institute.

Mexico

Reefs border the state of Quintana Roo on the east coast of the Yucatan Peninsula. The coastline is noted for its lack of surface rivers, although there are abundant subsurface flows within the limestone terrain. Coral reefs along the Mexican Caribbean coast consist of partially submerged

fringing reefs on the northern Yucatan coast and fully developed fringing reefs, with well developed and extensive spur and groove systems from Xcalak to Belize. The presence of the Xcalak trench has fostered the development of twin reef crests and fore-reefs in this area. A wide carbonate shelf, influence from coastal upwelling, and scattered patch reefs characterize the northern section. Offshore are three banks/islands: Arrowsmith Bank, along a submerged platform (ranging from 25-400 m in depth) with patch reefs on its southern section; Cozumel Island, with reefs on the windward and leeward side; and the Banco Chinchorro atoll with highly developed reefs on the windward side and well developed spur and groove systems.

Status of coral reefs prior to 2005: Puerto Morelos and nearby reefs suffered significant coral mortality from Hurricane Gilbert (1988) and the mass bleaching in 1995. Unlike the Belize reefs, the 1998 mass bleaching and Hurricane Mitch did not cause widespread coral mortality along the Yucatan coast. Patch reefs at Isla Mujeres and Cancun suffered some mechanical damage and fragmentation from Hurricane Ivan in 2004.

These reefs have suffered from intense fishing activities since the 1960s and increasing pressure from tourism since the mid 1970s. Reef patches at Punta Nizuc and El Garrafon at Isla Mujeres have already been affected by tourism-related activities and the damage appears to be spreading elsewhere to Akumal, Puerto Morelos, Mahahual and Cozumel. Shallow reefs at Cancun, Sian Ka'an and Chinchorro have been affected by boat-related damage. The reefs just off the northern tip of the Yucatan Peninsula and immediately westward (Punta Mosquito, Boca Nueva, Piedra Corrida) have very little (<2%) live hard coral cover.

Effects of the 2005 Bleaching Event: Coral bleaching was observed on Mahahual and Sian Ka'an reefs in late July by the Amigos de Sian Ka'an (Global Vision International) routine monitoring program. Although some bleaching was evident in almost twice as many colonies at Sian Ka'an compared with Mahahual, the number of colonies that were completely bleached at each site was low. Significant bleaching was observed during October by the Mesoamerican Barrier Reef System Project, with greater than 40% of colonies assessed on Xcalak reefs exhibiting some bleaching.

There was significant coral bleaching along the Yucatan coast of Mexico in 2005, but subsequent mortality was low (from MBRS Synoptic Monitoring Program, Xcalak; Amigos de Sian Ka'an-Global Vision International Monitoring Program, Sian Ka'an; and UQROO, Mahahual).

Location	Monitoring Timeframe (n = number of colonies assessed)	Colonies Affected by Bleaching (%)
Mexico (Mahahual)	July-September (n = 1532)	23
Mexico (Sian Ka'an)	August-September (n = 825)	42
Mexico (Xcalak)	October (n = 248)	45

Impacts of Hurricanes in 2005: The Yucatan Peninsula is frequently affected by storms and hurricanes. In the 20th century alone, 58 hurricanes (of varied strength) have passed along Mexico's Gulf and Caribbean coasts. These storms often resulted in significant reef damage from waves and the re-suspension of sediments. The reefs of Mexico suffered direct hurricane impacts

in 2005, with hurricanes Emily (17 July) and Wilma (21 October) hitting Cozumel, causing damage mainly to shallow coral reefs (< 8 m depth), including sponges and gorgonians.

There was a dramatic increase in bare rock substrata along Cozumel's west coast after hurricanes Emily and Wilma (July and October, 2005) increasing from 10% to 40% coverage, as a result of the removal of sand and benthic biota. Conversely, hard coral cover decreased after each hurricane from 24% to 17% and eventually down to 10%. After Emily, piles of broken coral colonies were seen scattered around the reefs, while after Wilma the coral rubble was removed from the reef areas, probably because of the long duration and high intensity of that hurricane.

Reefs off the northern Yucatan tip were also affected. Deeper reefs sustained little damage, with some sedimentation increases down to 15-20 m; although the sediments were usually removed by currents within a few weeks. In Cancún and Puerto Morelos, impacts were mainly on the reef crest and primarily to branching, boulder and mound hard corals. Restoration of fragmented pieces was carried out shortly after for reefs within Cancún and Puerto Morelos Marine Parks.

Status of reefs in 2006: Minimal bleaching was observed on Mahahual and Sian Ka'an reefs in 2006; about 5-6% of 1858 assessed colonies were affected. The reefs seem to have recovered from the 2005 bleaching event, and the disease and recent mortality values were very low; coral cover recorded at 121 sites (n = 3113 colonies) along the Mexican Caribbean (Amigos de Sian Ka'an and The Nature Conservancy /WWF 2006 Rapid Reef Assessment) was unusually low. However, this may be related to the representative sampling design, which included many marginal reef sites and only a few sites with coral cover values around 20-30%.

Low levels of recently diseased or dead corals were assessed on the Quintana Roo reefs (from Isla Contoy to Xcalak, including Cozumel and Banco Chinchorro) in September 2005 – December 2006 during the Amigos de Sian Ka'an and TNC/WWF Rapid Reef Assessment.

Reef Habitat (n = number of colonies assessed)	Coral Cover (%)	Colonies Affected by Disease (%)	Recent Colony Mortality (%)
Fore-reef (n = 1886 colonies)	8	0.9	1
Reef flat (inter-tidal (n = 704 colonies)	6	0.2	0.8
Patch reef & others (n = 523 colonies)	9	1.0	0.9

Sand beaches from Punta Cancun to Punta Nizuc were lost as a result of Hurricane Wilma in late 2005. In February 2006, the municipality implemented a project to restore the beaches; however, this project resulted in the die-off of 10 species of hard corals in Punta Nizuc owing to erosion of the reclaimed beach areas.

Socioeconomic impacts and management responses: Mexico's Caribbean reefs function as critical fishing grounds for communities along the Quintana Roo coast. These reefs are also the center of tourism activities; 8 MPAs have been established to protect reefs, and there are new MPAs proposed, including Playa del Carmen, Akumal, Puerto Aventuras and Tulum and Cozumel.

Guatemala

Guatemala has limited reef development along the Caribbean coast, with the best known being the carbonated banks of Punta Manabique, which are dominated by sediment resistant corals species such as *Siderastrea siderea*, and the isolated coral communities and diminutive patch reefs of the Gulf of Honduras.

Status of coral reefs prior to 2005: There has been significant degradation of Guatemalan reefs because of the combined effects of hurricanes, flooding and associated sedimentation, and increases in sea surface temperature. The major threat to the reefs of Punta Manabique is sedimentation resulting from deforestation and soil erosion, which bring elevated sediment loads and contaminants onto reefs, causing increased coral mortality and algal proliferation. A study conducted in 2000, recorded live coral cover of less than 9% and non-coralline macroalgal cover of 65%.

Effects of the 2005 Bleaching Event: The only monitoring data on the bleaching in 2005 were obtained in late November at Punta Manabique with 16% of 31 colonies being affected (data from the Mesoamerican Barrier Reef System Project, Synoptic Monitoring Program).

Impacts of Hurricanes in 2005: Like Belize, the reefs of Guatemala were not directly affected by the storms or hurricanes of 2005. However, increased sediment runoff associated with the torrential rains generated during the passage of Hurricane Beta near Honduras is likely to have had an impact.

Status of reefs in 2006: Based on a rapid assessment of 5 reef sites (145 colonies) in August 2006, the 2005 bleaching event did not appear to have made a significant impact on Guatemala's bank reefs. Recent mortality was less than 1%, while disease infestation was somewhat higher at 11%. Mean live coral cover was low overall, averaging 8.5% and similar to that found in 2000. Mean fleshy macroalgae cover was recorded at 7.3% and turf at 23.4%.

Socioeconomic impacts and management responses: River inputs of nutrients and sediments resulting from land erosion impede reef growth. Those reefs that do exist are subjected to intense fishing pressure and currently have minimal fish populations. Guatemalan fishermen are increasing fishing pressures on the southern reefs of Belize.

Honduras

While only small coral reef communities occur on the Caribbean coast of Honduras (Puerto Cortes, La Ceiba and Tujillo), there are well developed reefs on the outer Bay Islands (Utila, Morat, Barbareta, Roatàn, and Guanaja) and Cayos Cochinos. Well developed fringing and patch reefs are also found eastward (Misquitú Cays and Banks) and further northeast of the mainland (Swan Island). The edge of the Honduran continental shelf is almost vertical and has high coral cover.

Status of coral reefs prior to 2005: *The Global Coral Reef Atlas* reports average coral cover of 28% on the fore-reefs of the Bay Islands in the early 1990s. A 2001 WWF survey found average fore-reef live coral cover in Roatan/Barbareta of 12%, with 8% in Cayos Cochinos, somewhat lower than the MAR-wide average of 15%. This same study found the prevalence of

coral disease in Honduras was slightly higher than the MAR-wide average (4.4% versus 3.4%) as was recent partial mortality (1.8% versus 1.6%). The reefs of the Bay Islands were considered to be relatively healthy prior to the 1998 mass bleaching event and Hurricane Mitch. These events resulted in 18% coral mortality on shallow reefs and 14% on deep reefs, along with a high prevalence of coral diseases. Hurricane Mitch contributed to this damage via mechanical damage from waves and coral smothering from sediment-laden runoff. Hurricane Iris in 2001 also affected Honduran reefs through increased river runoff and sedimentation.

Effects of the 2005 Bleaching Event: No data on the extent of the 2005 bleaching event (during the event) were available to the authors. The MBRS Synoptic Monitoring Program reports data from one site (Utila) collected in February 2005 (before the bleaching season). The reef status indicators for 2006 show some signs of elevated disease and bleaching. However, without any data on the extent of bleaching during the 2005 bleaching season, no potential relationships can be considered.

Impacts of Hurricanes in 2005: The 2005 tropical storms probably reduced the temperature of overlying reef waters and decreased the severity of bleaching and associated mortality. However, some reefs may have been smothered by sediment plumes from runoff and mudslides originating from torrential rains, especially from those generated during the passage of Hurricane Beta.

Status of reefs in 2006: An assessment of 61 reef sites (1363 colonies) from early June to mid-August 2006 revealed some bleaching, but less than 11%. The prevalence of coral disease was rather high among the reef flat and patch reef sites, but recent mortality was less than 5%. Live coral cover was relatively low, averaging between 10% and 15%. Mean fleshy macroalgae cover was recorded at 15% on fore-reefs, 16% on patch reefs and 19% on reef flats.

There were moderate levels of coral bleaching, disease and mortality on the reefs of Honduras, predominantly resulting from the effects of hurricanes and to a lesser extent to increased water temperatures.

Reef Habitat assessed (n = number of colonies)	Colonies Affected by Bleaching (%)	Colonies Affected by Disease (%)	Recent Colony Mortality (%)
Reef flat (n = 373 colonies)	11	14	4
Fore-reef (n = 868 colonies)	4	9	2
Patch reef (n = 122 colonies)	8	18	2

Socioeconomic impacts and management responses: The Bay Islands’ reefs are the center for both tourism and fishing activities. Fringing reefs have been heavily exploited and the continued high demand for fish products has resulted in a relocation of fishing efforts to the more remote offshore reef banks. The Reefs at Risk project has estimated that 34% of Honduran reefs are threatened by anthropogenic stress, with the most pervasive being over-fishing (30%), coastal developments (25%), sedimentation from agricultural practices (10%) and marine based activities (6%). Enforcement of regulations aimed at protecting coral reefs and resource management is generally weak. Twelve MPAs have been developed, although a number of these are not legally declared or fully managed.

MESOAMERICAN REEF MANAGEMENT AND CONSERVATION EFFORTS

A number of regional conservation and management initiatives are being implemented to monitor, track, and promote the sustainable use and conservation of the MAR including: the Healthy Mesoamerican Reef Ecosystem Initiative; the GEF/World Bank Mesoamerica Barrier Reef System Project; The Nature Conservancy Mesoamerica Reef Program; and the WWF Mesoamerican Reef Ecoregional Program, and the ICRAN Mesoamerican Reef Alliance. There is relatively good collaboration among these and the many local conservation programs aimed at reducing threats to reefs and improving reef management. In 2006, these regional groups joined forces with numerous local partner organizations to conduct the largest regional assessment of reef health ever conducted in the region. More than 320 reef sites were surveyed in Mexico, Belize, Guatemala and Honduras using the 2006 AGRRA (plus) protocol. These data are being used for regional, national and local planning, management, and reporting efforts by the partner organizations.

If large-scale bleaching events continue to increase in frequency and severity, the coral reefs are likely to suffer further degradation. Whether these reefs will be able to maintain their ecological integrity will depend largely on their resilience, as well as the effectiveness of management efforts aimed at reducing other anthropogenic stress. Current and proposed bleaching management actions within the MAR are focused on identifying and protecting reefs that may be naturally more resistant to bleaching, have higher bleaching tolerance, and/or a greater ability to recover from bleaching (resilience), as well as traditional approaches for reducing or eliminating other anthropogenic stresses.

The areas that appear to be intrinsically resistant or resilient to bleaching can then be integrated within a regional MPA, which includes about 64 marine and coastal protected areas. These more resistant or resilient reefs may exhibit environmental (e.g. strong current or wave exposure, shading, etc.) or intrinsic factors (e.g. abundant heat-tolerant species) that help protect them from rising sea temperatures and allow them to potentially 'reseed' other reefs that are more affected by future bleaching events.

While traditional reef management efforts have focused on the management of MPAs, recent emphasis has been on the development of private sector partnerships aimed at promoting better management practices to reduce environmental impacts, particularly in tourism, fishing, agriculture and aquaculture industries.

CONCLUSIONS AND RECOMMENDATIONS

Although the number and scope of marine conservation programs has grown tremendously in the last decade, continued degradation from mass coral bleaching and hurricanes has the potential to prevent reef recovery and even further accelerate reef damage. Climate-related stressors, in combination with many increasing chronic anthropogenic stressors, could lead to unprecedented collapse of the Mesoamerican reef ecosystem and the many livelihoods that depend upon it. It has been suggested that the degree to which mass bleaching will affect coral reefs over the long term may depend on the extent of additional environmental stressors (over-fishing, pollution, habitat destruction), the degree to which corals are able to acclimate or adapt to the rising temperatures, the frequency of these disturbances, and whether these repeated disturbances compound each other. The MAR reef management community needs to increase

the understanding of how different coral reefs will respond to continued ocean warming. Such information can be incorporated into preventative strategies and aid in adaptive responses and monitoring.

There was no organized and immediate bleaching monitoring response to the 2005 bleaching event. Most of the planned monitoring efforts (MBRS Synoptic Monitoring) occurred before the main effects of the bleaching event in late October. There is an urgent need to establish a MAR 'Bleach Watch' rapid response program.

A Coral Bleach Watch Rapid Response Contingency Plan for the MAR would: i) incorporate the NOAA 'HotSpot' system of forecasting bleaching events into the local managers networks; ii) make available early warnings of any major bleaching episode; iii) measure the spatial extent and severity of large scale bleaching events through all phases of the event; iv) assess ecological impacts of such events (8 – 10 months later); v) involve stakeholders in reef monitoring activities; vi) enhance communication and awareness on bleaching and the effects of climate change on the MAR; and vii) provide critical information necessary to evaluate implications of bleaching events for management, policies and strategies.

Finally, managers need to continue to reinforce efforts to improve watershed management and enforcement of fishing, tourism and coastal development regulations, to reduce the stress on coral reefs to provide them with a better chance to recover from bleaching events.

The *Healthy Mesoamerican Reef Ecosystem Initiative* is a multi-institutional effort that generates user-friendly tools to measure the health of the Mesoamerican Reef Ecosystem, and delivers scientifically credible reports to improve decision-making that effectively sustain social and ecosystem well-being. The Initiative focuses on three over-arching goals:

- Promoting the adoption and application of **eco-health and socioeconomic indicators** by managers, policy makers and other leaders concerned with the integrity of the Mesoamerican Reef Ecosystem;
- Providing **standardized analyses** of reliable scientific data to improve reef ecosystem management; and
- Serving as a **clearing house** for information and networking among science and conservation partners to improve environmental management and stewardship of reefs.

Annual Eco-health Report Cards and triennial State of the Reef Reports will be a mainstay of this growing Initiative, which recently published the seminal publication, *Guide to Indicators of Reef Health and Social Well-being in the Mesoamerican Reef Region*. This publication and other information on the Initiative are available from www.healthyreefs.org.

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6. CORAL REEFS OF THE U.S. CARIBBEAN

THE HISTORY OF MASSIVE CORAL BLEACHING AND OTHER PERTURBATIONS IN THE FLORIDA KEYS

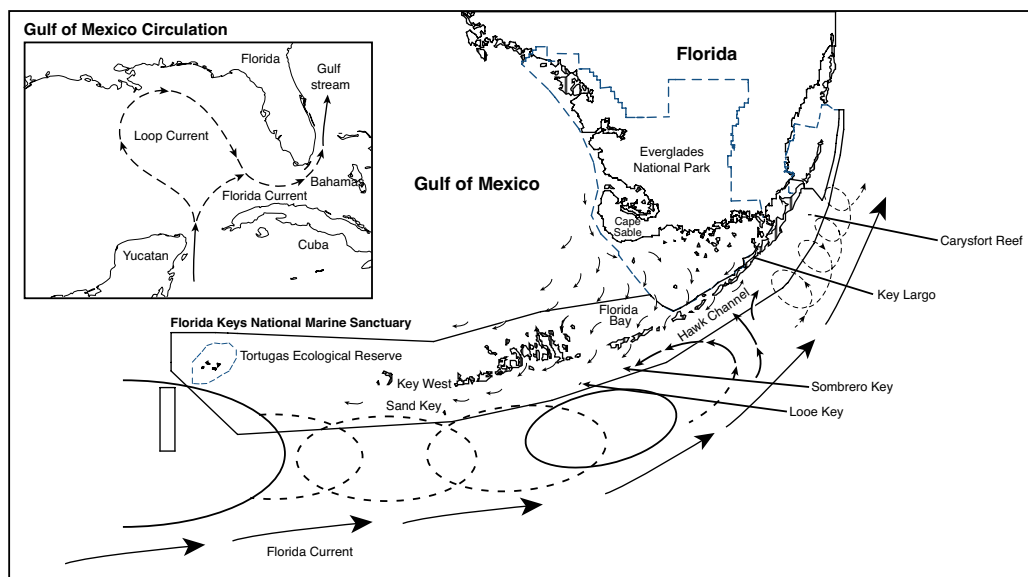
BILLY CAUSEY

INTRODUCTION

The extensive offshore coral reefs (patch, offshore bank or bank barrier, transitional and deep reefs), fringing mangroves, seagrass meadows, and hard-bottom areas, are protected as the Florida Keys National Marine Sanctuary; the third largest marine protected area in the USA. These resources are the basis for the economically important commercial fishing and tourism located in south Florida, which attracts more than 4 million visitors who spend in excess of 14 million visitor-days per year. Most are snorkelers and scuba divers, as well as recreational fishers and water sports enthusiasts. Others come to the Keys to relax and enjoy the tropical climate of a unique destination.

The waters surrounding most of the 1700 islands of the Florida Reef Tract (here called the Florida Keys), which are arranged in a 320 km (220 mile) arc, were designated a national marine sanctuary in 1990 to stem mounting threats to the health and ecological future of the coral reef ecosystem. More than 60% of the Sanctuary (9800 km²; 2900 square nautical miles) is in State of Florida waters, and the Sanctuary is managed through a co-trustee management agreement between the State of Florida and the national government, via the National Oceanic and Atmospheric Administration (NOAA).

The Florida Reef Tract region is warmed by the Florida Current flowing from the Caribbean and the Loop Current from the Gulf of Mexico, enabling major reef building corals and reef species to inhabit such northern latitudes. The coral reef community of the Florida Keys is vulnerable to both natural and anthropogenic impacts, including: extreme changes in sea surface temperatures; coral diseases; increased sedimentation; exposure to pollution from the land; habitat degradation and loss resulting from coastal development; over-fishing; and excessive visitor use. However, the overwhelming threats to the coral reefs have been coral diseases and increasing sea surface temperatures (SSTs) over the past 28 years. This thermal stress has been exacerbated by other anthropogenic pressures on the ecosystem.



The net flow of seawater of the Florida Current is from the Gulf of Mexico and Caribbean along the Florida Keys. The progression of gyres rotating counter-clockwise entrains waters from Florida Bay and the Gulf of Mexico that influence reef areas of the Lower Keys (illustration from Tom Lee/ University of Miami, RSMAS)

HISTORY OF CORAL BLEACHING IN THE FLORIDA KEYS

The first observations of massive coral bleaching in the Florida Keys were in the 1980s; these were associated with elevated SSTs. A combination of stress events, such as cold water stress from winter fronts, brief warm water events, or reduced light penetration during lengthy periods of turbid water, occurred in the 1970s. In 1977, an enormous die-off of the branching coral *Acropora* occurred as a result of a severe cold front that hit the Keys. These periodic short-term coral bleaching events reported in the 1970s were possibly preceded by similar episodes in the 1950s and 1960s. However, a pattern of intensifying coral bleaching and other marine stresses has occurred since the late 1970s.

1979: The first sign of stress on the outer coral reefs was a die-off of sponges in June-July 1979, with a massive loss of the barrel sponge, *Xestospongia muta* on Big Pine Shoal, south of Big Pine Key. Hundreds of large sponges disintegrated during a month when extraordinarily warm waters flowed from the Gulf of Mexico across the reefs.

1980: In June-July 1980, doldrum-like weather patterns replaced the normal summer trade winds; the skies remained clear and almost cloudless and the seas were very calm for 6 weeks. Within a few weeks, angelfish, surgeonfish, butterflyfish and some other reef fish showed signs of extreme stress; they were respiring heavily and could be collected by hand. Open wounds and disease were commonly seen on the fish and large numbers began dying throughout the Keys. During the fish die-off, minor coral bleaching was noted on offshore coral colonies, which appeared mottled and lighter in color than normal. There was no uniform bleaching during this episode.

1982-1983: Elevated SSTs continued in the Florida Keys and nearby reefs. In November 1982, coral reefs on the Pacific side of Panama were severely bleached, with considerable coral mortality. Record SSTs on the Pacific and Caribbean sides of Panama were thought to be the trigger for the massive die-off of the long-spined sea urchin, *Diadema antillarum* that occurred throughout the Wider Caribbean in 1983-84. About 95% of these important algal grazers died in a single year.

In July 1983, doldrum-like conditions returned to the Florida Keys at the same time the urchins (*Diadema*) were dying in what was then the Looe Key National Marine Sanctuary. The corals began turning white after only a couple of weeks of these conditions. This first mass coral bleaching spread along the seaward part of the outer coral reef tract from Big Pine Key to Sand Key Reef off Key West. Coral bleaching was most severe on the shallow fore-reef habitats, and especially on the outer shallow reefs in the lower Florida Keys where there is the greatest exposure to currents from the warmer waters of the Gulf and Florida Bay. In this area of the Keys, the net flow of water is from the Gulf, through the passes and in an offshore direction toward the reef tract. This current pattern bathes the coral reefs along the reef tract from Looe Key Reef to Sand Key with water from the Gulf and Florida Bay.

1986: In May and June 1986, there was an alarming outbreak of black-band disease on fore-reef coral colonies at Looe Key Reef. Coral colonies of all sizes were affected in an area that matched the footprint of the 1983 mass coral bleaching event. There had been very few sightings of black-band disease prior to this at Looe Key Reef. However, in 1986, this disease killed coral colonies that were more than 200 years old.

1987: Similar doldrum-like weather patterns re-occurred in the Florida Keys in June 1987. In mid-July, corals at Looe Key Reef turned mustard yellow or were mottled or pale. By mid-August, a mass coral bleaching event was occurring on the outer reefs of the entire Florida Reef Tract. In late September, there were reports of coral bleaching throughout the Caribbean. In mid-October, reports of coral bleaching in the Indo-west Pacific were coming in from coral reef managers and scientists; coral bleaching had become a global, synchronized event.

The primary significance of the 1987 bleaching event in the Florida Keys, compared with the 1983 event, was the broad extent of the coral bleaching along the seaward margin and on the outer reef tract throughout the Keys. There was also significant bleaching of corals at greater depths, but still restricted to the same area (outer reef tract). Corals from very shallow water down to depths of 30 m were almost uniformly white. This concurrence of widespread bleaching throughout the Caribbean and Indo-west Pacific in 1987 prompted the US Congress to hold a hearing in November 1987 on coral bleaching. In April 1988, a workshop on coral bleaching co-chaired by John Ogden and Bob Wicklund was held in St. Croix, U.S. Virgin Islands to advise government on potential future management action.

1989: There was a minor coral bleaching event in August 1989. This was restricted to the genus *Agaricia*, and only on the fore-reef at Looe Key Reef. The event lasted about 6 weeks, and there were similar reports of *Agaricia* bleaching in Puerto Rico and Lee Stocking Island in the Bahamas.

1990: More doldrum-like weather patterns with calm seas returned to the Florida Keys in July 1990. Early signs of bleaching were seen in the zoanthid, *Palythoa caribaeorum*, which turned

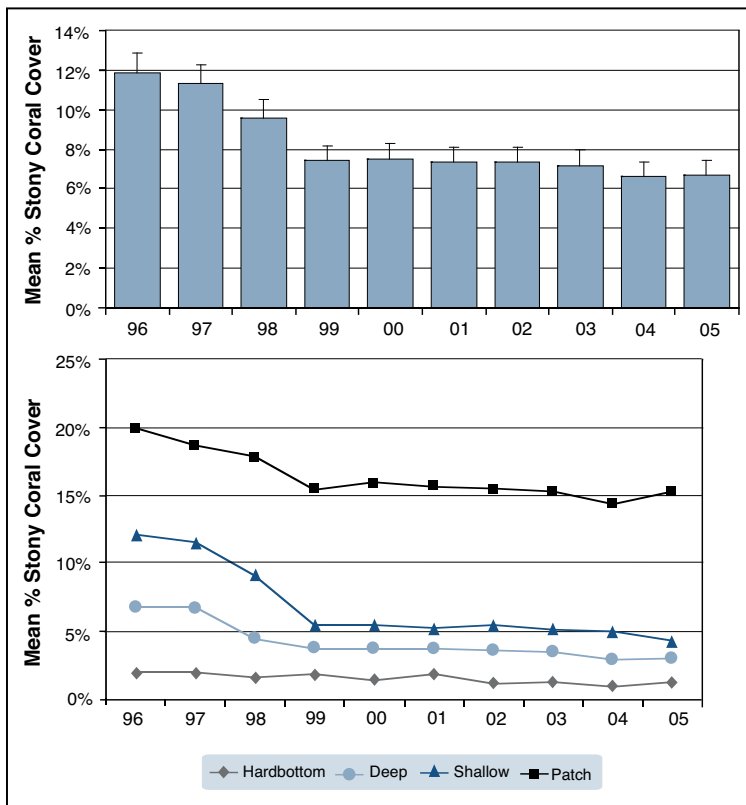
pale white, and the polyps completely closed shortly before the stony corals bleached. In early August, corals began to bleach on the outer reef tract starting at Looe Key Reef. By mid-August, there was coral bleaching on the inshore patch reefs and in the tidal passes. This was the first time mass coral bleaching had extended to inshore waters. The shallow coral colonies at Looe Key Reef were severely bleached for 2 months; their fate was followed by monitoring. There was a substantial loss of living coral, with more than 65% mortality of fire coral (*Millepora complanta*) on the shallow reef crest. Similar anecdotal reports came from other shallow reefs, from Key Largo to Key West.

These nearshore coral reefs regularly experience higher and lower water temperatures than offshore corals and have acclimated over geological time to tolerate a broader range of temperatures. It appears that, unlike earlier mass bleaching events, SSTs during 1990 exceeded the upper temperature thresholds of acclimated inshore coral colonies. The 1990 coral bleaching event was significant because it was the first time that corals in nearshore waters had been affected by a mass bleaching episode and the first time that the large-scale loss of corals in the Florida Keys could be directly attributed to coral bleaching.

Although there was no mass coral bleaching in the Florida Keys between 1990 and 1997, there were wide-spread outbreaks of various diseases that affected both branching corals (*Acropora*) and boulder corals (*Diploria*, *Montastraea*, etc.). The *Acropora* species, especially elkhorn coral (*Acropora palmata*), were most affected by the outbreaks, with large amounts of living coral tissue killed by various diseases (e.g. white-band, white plague, white plague type II, etc.). There were also fish disease outbreaks in the Florida Keys and other parts of the Caribbean. The symptoms and species affected closely resembled the 1980 fish die-off; the disease agent was a fungus, *Brookynella*, which affects tropical reef fish during environmental stress.

1997-1998: Doldrum-like weather conditions returned to the Florida Keys in July 1997 and by mid-August, a mass coral bleaching event was underway. Once again, the bleaching event was widespread and heavily damaged the inshore corals. Third generation residents raised the alarm and reported to Sanctuary managers that such bleaching was unknown in the Florida Keys in recent history. The 1997 coral bleaching event was extensive and long-lasting, and affected both offshore and inshore corals, with many remaining bleached or mottled well into 1998. Previous bleaching events had subsided by November. However, waters of the Florida Reef Tract did not cool much during the winter of 1997-98 and the unseasonably warm water of 1997 continued into early 1998. The doldrum-like weather patterns started early in 1998, and the warm water persisted even when the wind blew, unlike previous years.

Coral bleaching in the Florida Keys and other parts of the tropical world during 1997-98 was the first ever back-to-back event, with local, regional and global scale damage similar to the 1987 and 1990 episodes. Bleaching on remote Pacific islands coincided with devastating bleaching in the Florida Keys and the tropical North Atlantic (Wider Caribbean). The Florida Keys were then hit by Hurricane Georges in September 1998 and Tropical Storm Mitch, just as the bleaching was being assessed. In addition, there were outbreaks of the fish disease *Brookynella*, similar to 1980, killing angelfish, butterflyfish and other reef species. Similar reports came in from other areas of the Wider Caribbean.



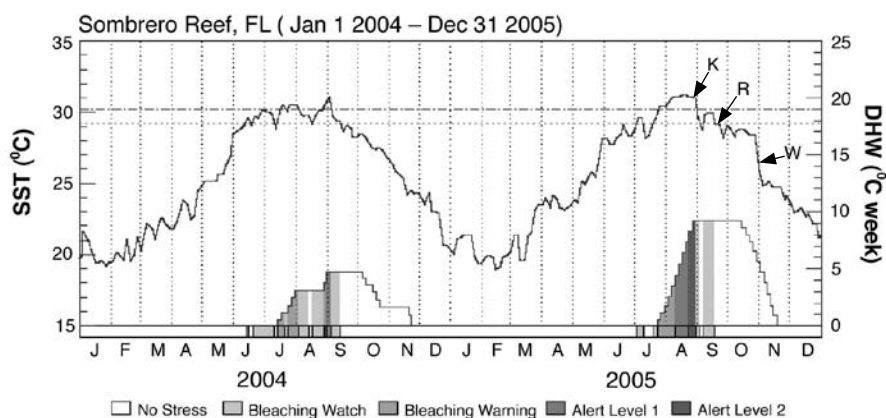
There has been an almost continual decline in coral cover in the Florida Keys in all habitats since 1996, with a mean decrease from 11.9% cover in 1996 to 6.7% in 2005. The hard-bottom habitat usually has a low cover of isolated, small coral colonies alongside gorgonians (octocorals), sponges and other organisms; but this habitat makes up the largest proportion of rocky substrata within the Sanctuary. These data have been collected at multiple stations with 43 fixed sites along the Florida Keys, by the Florida Keys National Marine Sanctuary, US Environmental Protection Agency and NOAA since 1996, via the Coral Reef Evaluation and Monitoring Project (CREMP), which also involves the Florida Fish and Wildlife Research Institute and the University of Georgia. The top figure shows a precipitous decline in bleaching years with a leveling-off of coral cover since the 1997-98 bleaching events and the hurricanes of 1998, 2004 and 2005. The lower graph shows the same precipitous decline in all coral habitat types between 1996 and following the 1997-98 bleaching events and subsequent coral disease outbreaks. Coral cover is higher in the patch reef areas compared with offshore reefs. The patch reefs have been exposed to broader ranges of sea surface temperatures, sediments and nutrients over a much longer timeframe i.e. centuries compared with decades (data from www.floridamarine.org).

The greatest loss of coral cover has been on the shallow, spur and groove bank-reefs, where most diving occurs. One could speculate that the diving was the cause of this loss, but the largest decline has been on Carysfort Reef in the Upper Keys where dive pressure is low. However, diving remains on the list of cumulative stresses to coral reefs.

The shallow offshore reefs have existed for decades within a narrow range of seasonal temperatures, salinity, and sedimentation. Recently, the maximum SST has often exceeded 31°C during July and August when doldrum weather patterns set in for long periods. The

shallow reefs bleached first and remained bleached for longer, thus excessively stressing the coral colonies. The largest decline in coral cover occurred following 1997 and 1998; since then coral cover has remained low and relatively constant.

While there has been relatively little decline in coral cover since 1999, there has been little new coral recruitment. Thus, it appears that the same environmental and water quality problems that contributed as secondary stresses causing the loss of coral have also prevented recovery by new coral recruits. Another factor was the loss of algal grazing *Diadema antillarum* in 1983; macro-algae now cover much of the reefs preventing the settlement of new coral recruits, and increasing competition for space amongst various reef organisms. While there has been some coral recruitment, it has been insufficient to prevent the reefs from becoming increasingly barren of living corals.



Three hurricanes passed near the Florida Keys in 2005. SSTs (recorded at a SeaKeys C-Man station on Sombrero Reef) rose to more than 31°C in July, but the passage of Hurricanes Katrina (K), Rita (R) and Wilma (W) reduced elevated SSTs, alleviating the stressful conditions and resulting in minimal coral bleaching (image from Mark Eakin NOAA/NESDIS).

There are more than 9000 patch reefs in the Upper Keys; these have shown the least decline in coral cover and are still the most extensive coral communities. The patch reefs occur in very turbid, shallow inshore waters of the Keys, through Hawk Channel and to the outer reefs. They grow in waters with the highest levels of nutrients in the Sanctuary and are seasonally exposed to the warm waters of the Gulf of Mexico. These waters get very cold in winter and very warm in summer, but the patch reefs have acclimated to the widest range of environmental conditions in the Florida Keys. There are 200 - 300 year old coral colonies that are unblemished from diseases. These are the only reefs that have shown any increase in coral cover during the last 10 years.

Other reef animals are also disappearing in the Florida Keys; for example, the corallimorph, *Ricordea florida*, (also known as false coral) was abundant on shallow reefs such as Looe Key Reef in the 1960s and 1970s, but began to disappear from Looe Key Reef in the early 1980s. Most of the populations had vanished from the shallow reefs by the time monitoring started in 1996. There are anecdotal reports that crinoids have also disappeared from the reefs. These

were frequently seen on shallow reefs like Looe Key Reef in the 1960s and 1970s and were common at 20 to 40 m on deep reefs. A survey in September 2001 between 20 and 30 m found none during 6 hours in areas where crinoids were previously abundant. However, crinoids are still seen on the reefs in the Tortugas Ecological Reserve, to the far west of the Sanctuary, in waters that have been less influenced by elevated SSTs and land-based sources of pollution, indicating that crinoids are another group affected by higher SSTs and pollution.

2004-2005: Although elevated SSTs occurred in the Florida Keys in 2004 and 2005, there was only minor to patchy coral bleaching. The corals escaped the severe coral bleaching that was recorded throughout much of the Wider Caribbean. Both 2004 and 2005 were active hurricane seasons; each tropical storm reduced SSTs, by mixing the surface waters with deeper, cooler waters.

CONCLUSIONS

Coral bleaching has been intensifying over the past 25 years at the local scale in the Florida Keys; this is consistent with other observations at regional and global scales. The pattern and intensity of coral bleaching events has shown a spatial and temporal expansion during this time, with concurrent increases in secondary impacts, such as coral diseases, loss of living tissue and low recruitment on the coral reefs of the Florida Keys. The shallow bank-reef habitats have been most severely affected, probably because they have historically existed in a narrower range of environmental conditions. In contrast, patch reefs, which are regularly exposed to elevated nutrient and sediment levels and broad seasonal fluctuations in water temperature, have been least affected and have retained the highest living coral cover. These corals have probably survived the bleaching episodes because they are better adapted to a broad range of physical conditions, similar to those that occur during doldrum-like weather. The mechanism is unclear; it is possible that natural selection has influenced their genetic composition so that they are able to tolerate greater fluctuations of temperature and nutrient levels, and lower light conditions.

Coral reefs of the Florida Keys are affected by the same stresses damaging reefs worldwide: climate change; diseases; land-based sources of pollution; habitat loss and degradation; and over-fishing. There is no longer a debate that coral bleaching is linked to global climate change; and a few people debate the causes of global climate change. Irrespective, coral reef scientists and managers need to take every possible immediate action to preserve and conserve the coral reef resources of the world. While such scientific debate is healthy and part of the scientific process, there comes a time when debate seeking second opinion distracts from the obvious, and provides decision-makers with a no-decision option. The suspected causes for the coral loss in the Florida Keys have varied enormously over the years; now there is recognition that elevated SSTs are the primary cause of coral bleaching. A minority viewpoint has focused on land-based sources of pollution as the cause of coral decline. Clearly, both have played a major role in the decline of coral reefs on a global scale; research should be focused on unraveling the causes of coral decline at scales from microbial to the ecosystem.

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CORAL BLEACHING IN THE U.S. VIRGIN ISLANDS IN 2005 AND 2006

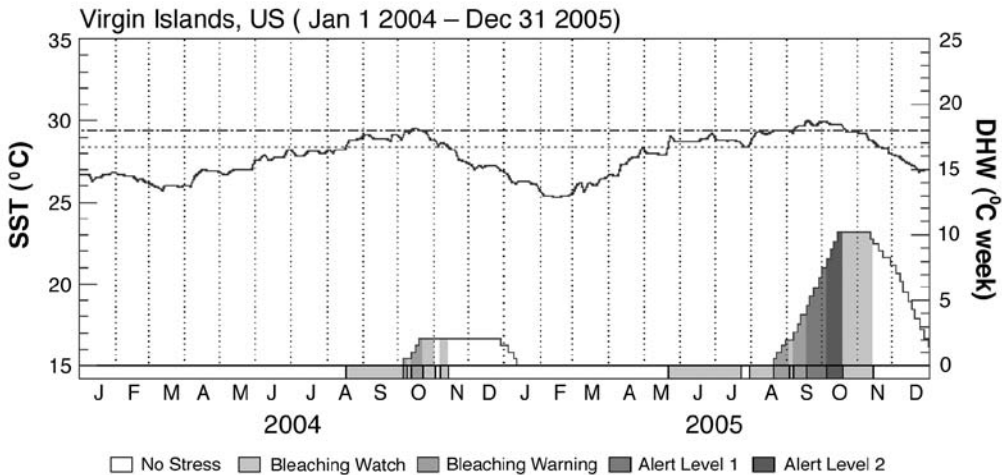
KIMBERLY WOODY, ANDREA ATKINSON, RANDY CLARK,
CHRIS JEFFREY, IAN LUNDGREN, JEFF MILLER, MARK MONACO,
ERINN MULLER, MATT PATTERSON, CAROLINE ROGERS, TYLER SMITH,
TONY SPITZAK, ROB WAARA, KEVIN WHELAN, BRIAN WITCHER AND
ALEXANDRA WRIGHT.

SUMMARY

- Severe coral mortality occurred in the U.S. Virgin Islands (USVI) between July and November, 2005 because of bleaching and disease; the average decline in hard coral cover was 51.5%;
- Sea surface temperatures exceeded the 29.5°C coral bleaching threshold for 12 weeks in 2005; maximum temperatures exceeded 30°C. The reefs suffered more thermal stress during this period than during the previous 20 years combined;
- Coral bleaching was observed between July and November, 2005; on average it affected more than 90% of the coral cover;
- Bleaching occurred in 22 coral species over a wide range of depths;
- The greatest bleaching-related mortality occurred in the genus *Agaricia*; bleaching also severely affected *Montastraea*, *Colpophyllia*, *Diploria* and *Porites*, but mortality in these species was usually the result of subsequent infection by white plague or white syndrome;
- Coral losses in late summer 2005 were more severe than any time in the last 40 years.

INTRODUCTION

The first indications of potential thermal stress to the corals of the USVI occurred in July 2005 with observations of bleached corals, and in August when satellite information provided by the National Environmental Satellite, Data, and Information Service (NESDIS) Coral Reef Watch indicated that sea surface temperatures (SSTs) in the north-eastern Caribbean were higher than normal. Temperatures continued to rise, producing more thermal stress during this single period than during the previous 20 years combined (Coral Reef Watch 2005, accessed 19 November 2007). The bleaching threshold of 29.5°C (83.3°F) was exceeded for about 12 weeks prior to 12 November 2005, with SSTs reaching just over 30°C; a full degree warmer than the previous year. This chapter discusses how monitoring efforts in the USVI captured the bleaching event of 2005 and demonstrates that several methods used to monitor the health of the reefs arrived at the same conclusion: coral cover on USVI reefs is declining.



Sea surface temperatures (SSTs) in 2005 exceeded those of 2004, especially between August and November (solid line) when they exceeded the coral bleaching threshold of 29.5°C in the USVI (dashed line). The accumulation of ‘Degree Heating Weeks’ (DHW) is shown along the X-axis in red along with the timing of bleaching watches and warnings issued in 2004 and the major alerts in 2005 from August to November. The thermal condition is categorized according to the five bleaching alert levels defined by Coral Reef Watch’s Satellite Bleaching Alert. Source: http://coralreefwatch.noaa.gov/satellite/current/sst_dhw_series_usvirgin_cur.html

EFFECTS OF THE 2005 BLEACHING EVENT

Declines in coral cover and increases in macroalgae resulting from a variety of stresses including hurricanes and coral disease have been reported previously in the USVI. For example, major coral losses occurred in the 1970s and 1980s as a result of white band disease, killing more than 90% of *Acropora cervicornis* and *A. palmata* colonies, the primary shallow water reef building corals. However, the 51.5% decline in mean coral cover during the 12 months following the major 2005/06 bleaching and disease event was unprecedented. These losses occurred on well developed ‘high’ coral cover, high coral diversity reefs being monitored by the National Parks Service. Even deep reefs with high coral cover (>30% cover, >30 m) were affected by bleaching and disease.

National Park Service Inventory and Monitoring (NPS I&M) and US Geological Survey (USGS) scientists documented the effects of the 2005 bleaching and subsequent coral disease at long-term monitoring sites around St. John and St. Croix. An average of 90% of the coral cover bleached at 5 permanent sites (100 transects at depths between 4 m and 19 m) in St. John and St. Croix, including Virgin Islands National Park (VINP) and Buck Island Reef National Monument (BIRMN). By late 2005, many of the corals began to regain color; but then became infected by the white plague coral disease. In just one year, the average decline in coral cover at these sites was 51.5% (range 34.1% - 61.8%). There were massive declines in the major reef building coral species: the *Montastraea annularis* (complex) once comprised 80% of the total coral cover, but suffered a 51% decline compared with pre-2005 levels; the cover of *Agaricia agaricites*, *Colpophyllia natans* and *Porites porites* declined by 87%, 78%, and 48% respectively. However, there was no change in cover of *M. cavernosa*. While mortality of *A. agaricites* was directly attributable to bleaching, mortality in nearly all other coral species

resulted from subsequent infection of white plague disease. The average number of species per transect also declined by 21%.

Agency	Region	Category	% Bleaching	% Mortality
NPS I&M / USGS	St. Croix, St. John	Overall	90	51.5
		<i>A. agaricites</i>		87
		<i>C. natans</i>		78
		<i>M. annularis</i> (complex)		51
		<i>P. porites</i>		48
NPS / USGS	St. Croix, St. John	<i>Agaricia</i> spp.		87*
		<i>C. natans</i>		35*
		<i>Diploria</i> spp.		17*
		<i>M. annularis</i> (complex)		12/55*
		<i>P. porites</i>		15*
UVI	Region-wide	Overall	57	40
		<i>Montastraea</i> reef - total loss		70-90
		<i>Montastraea</i> reef – <i>Montastraea</i> loss		83-95
BB / NPS	St. Croix	October	53	
		December	28	
USGS	VINP	<i>A. palmata</i>		15/36
NPS	BIRNM	<i>A. palmata</i>	79.8	58.1

Summary of results of surveys conducted by several agencies (explained in the text) to determine the impacts of the 2005 bleaching / disease event in USVI. * indicates that percentages have been calculated as the proportion of the total number of colonies of each coral species surveyed. All other percentages have been calculated from coral cover data. Where two values are separated by /, the first value reports the percentage cover or proportion of colonies that suffered complete mortality, and the second reports the percentage of partial mortality.

The fate of 4153 coral colonies on the 100 transects was tracked by NPS and USGS. Colonies of *Agaricia* spp. were the most severely affected by bleaching with 87% mortality, and 35% of *C. natans*, 17% of *Diploria* spp. and 15% of *P. porites* colonies had died within 6 months of the peak bleaching in September 2005. The *M. annularis* (complex) initially exhibited substantial recovery from bleaching, but subsequently, there was high mortality as a result of white plague coral disease, with 12% of colonies dying completely and about 55% showing partial colony mortality.

Bleaching and mortality in territorial waters followed a similar pattern to that observed within the national parks. Researchers from the University of the Virgin Islands reported an average of 57% of the coral cover bleaching (74% of individual colonies) at a range of depths, which resulted in only a 4% decline in coral cover. However, there was a subsequent increase in tissue-eroding white syndrome, from 0.5% of colonies infected prior to and during bleaching, to 4% after the bleaching. This was probably responsible for a 40% decline in coral cover across the territory. In two deep (20-30 m) areas that formerly had high *Montastraea* cover (~36%), there was a 70-90% decline in total coral cover, resulting predominantly from the loss of *Montastraea* (83-95% cover loss).

At 30 m depth along this *Montastraea* reef system, NCCOS/Biogeography Branch (BB) and NPS recorded a significant decrease in average coral cover between 2005 and 2006, from 8.69% (± 1.6) in 2005 to 6.60% (± 1.3) in 2006, representing a 24% decline in coral cover. The difference between this estimate and the 70-90% decline described above is most likely explained by the patchy spatial distribution of corals along this reef system and differences in sampling techniques. The overall conclusion is that coral cover declined significantly between 2005 and 2006.

In October 2005, the BB and NPS BIRMN observed bleaching in 22 scleractinian coral species in north-eastern St. Croix, with nearly 53% of the coral cover bleached at 91 of 94 randomly selected sites (depth range 3-28 m). The average coral cover at these sites was 5.6%. Bleaching was widespread, with no obvious spatial pattern. Coral species most affected by the bleaching event included *D. labyrinthiformis*, *Agaricia* spp., *Mycetophyllia* spp., and *M. annularis*. By December 2005, bleaching was still evident, with colonies at 15 of 18 randomly selected sites still bleached. Only 28% of the 3.9% total coral cover was bleached, and an additional 4% colonized by cyanobacteria or other algae (i.e. recently dead), but there was evidence of corals recovering from bleaching.

The first time that bleached *A. palmata* colonies had been observed in the USVI was in July 2005, with 50% of 460 colonies in VINP, St. John showing some bleaching. This eventually resulted in 36% (± 7.4) of colonies suffering partial mortality and 15% (± 8.5) dying completely. Mortality of *A. palmata* rose during 2005, but was not always directly related to bleaching. Isolated incidences of disease and bleaching contributed to the rise in mortality. Bleaching was not followed by severe outbreaks of disease except at one site, Hawksnest Bay, where a combination of disease and bleaching caused greater mortality within 3 months than other stresses (e.g. predation, physical damage) had caused during the previous 2.5 years. All surviving colonies regained normal coloration by February 2006.

There was also extensive bleaching of *A. palmata* in 2005 at BIRMN, St. Croix. Bleaching was observed between August 2005 and January 2006, with greatest bleaching recorded at South Forereef in November 2005, where 79.8% (± 9.1) tissue bleached, followed by 58.1% (± 9.8) tissue mortality. The greatest tissue mortality (66.4% (± 8.7)), occurred at the Underwater Trail. There was 36.4% (± 12.5) tissue mortality at the North Bar. Colonies on the back-reef appeared to be more affected than colonies elsewhere, raising the possibility that reduced water flow and calmer conditions exacerbated the bleaching and resulted in greater mortality.

CONCLUSION

The coral bleaching/disease event of 2005 added to the historical impacts of other stresses (pollution, over-fishing, physical damage), resulting in major damage to the reefs of the USVI. Management actions to improve water quality, prevent over-fishing and reduce physical damage and overuse may create a foundation for better reef recovery and long-term survival.

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7. THE EFFECTS OF CORAL BLEACHING IN THE NORTHERN CARIBBEAN AND WESTERN ATLANTIC

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VANIA COELHO, AYLEM HERNÁNDEZ, ROSS JONES, JENNIE MALLELA AND
CARRIE MANFRINO

SUMMARY

- The effects of bleaching and hurricanes on coral reefs in 2005 varied across the region and within countries.
- Some countries experienced intense widespread coral bleaching down to 35 m, while the effects of increased water temperatures were moderate to low in others.
- Coral mortality rates were low on average; most corals recovered quickly when water temperatures dropped.
- Greater human and financial resources are needed to monitor and effectively combat the effects of natural disasters.
- Regular monitoring and analysis of data are essential components of sound management strategies for sustainable environmental management and economic growth.

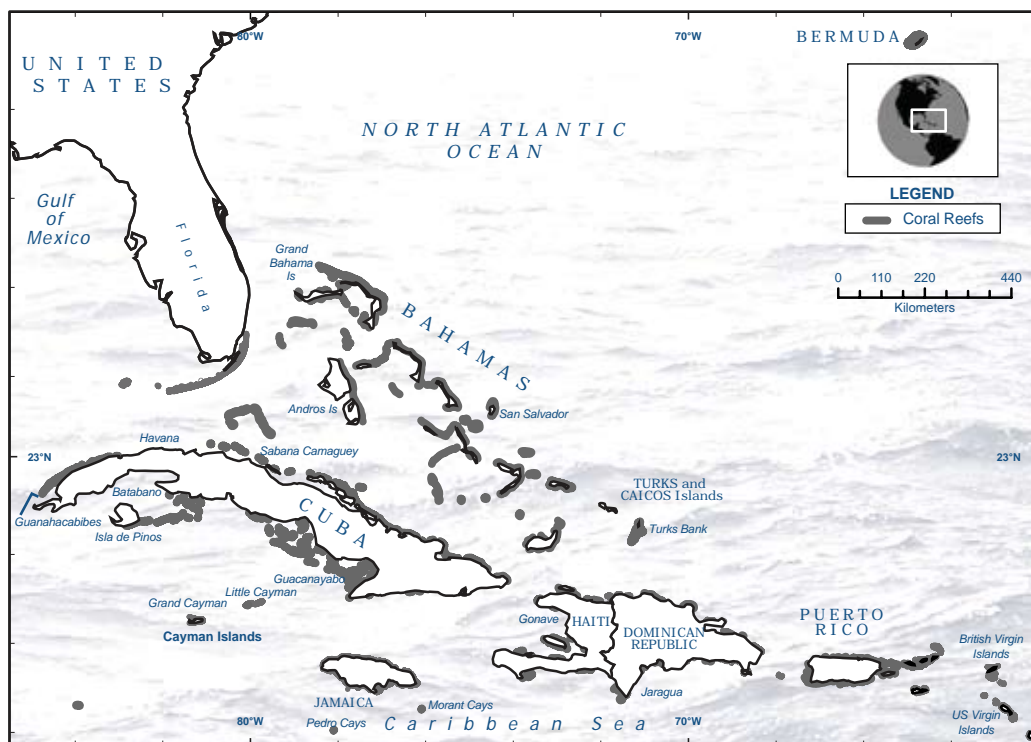
INTRODUCTION

Coral bleaching during the hot summer of 2005 hit the reefs of the Northern Caribbean (Bahamas, Bermuda, Cayman Islands, Cuba, Dominican Republic, Haiti, Jamaica, Turks and Caicos) just as they were recovering from many damaging stresses of the past 30 years. In the 1970s, the coral reefs generally had more than 50% coral cover, with large stands of branching corals; *Acropora palmata* on the reef crest, and *A. cervicornis* on the shallow fore-reef slopes. The first signs of over-fishing of groupers and large parrotfish were evident, but the reefs were predominantly healthy.

The Northern Caribbean reefs were degraded during the 1980s by outbreaks of coral diseases (especially white band disease of *Acropora*), mass mortality of the main algal grazer *Diadema*, nutrient and sediment pollution from activities on land, and severe coral bleaching and damaging hurricanes. Coral cover in most places dropped to 5-10%, and was replaced by fleshy and calcareous macro-algae, with cover often 50-80%. Since then, these Caribbean reefs have

been slowly recovering, however, coral cover was still low and the threats from increasing human populations and economic pressures continued to grow.

The first warning of problems came from NOAA in late May 2005 that indicated ‘HotSpots’ developing in the Northern Caribbean, especially around the Virgin Islands. These warnings alerted the scientists and NGOs in the region to examine their reefs in more detail. The results of subsequent surveys of bleaching and mortality in each country are summarized below.



Map of the Northern Caribbean region.

ECOLOGICAL AND SOCIOECONOMIC IMPACTS OF CORAL BLEACHING AND HURRICANES IN 2005

Bahamas

Geographic Distribution and Extent of Coral Reefs: The Bahamas contain 13 major islands and more than 2000 smaller islands or cays, distributed over 260,000 km² on 2 large, shallow banks (Great Bahama Bank and Little Bahama Bank) separated by depths exceeding 4000 m. They are aligned northwest to southeast for more than 1400 km, from near Florida almost to Haiti. Coral reefs fringe most of the north and east windward coasts and bank edges and cover 1832 km² of the Great Bahama Bank and 324 km² of the Little Bahama Bank. Andros Island is the largest island with the third longest barrier reef system in the world (229 km). Reef development in the Bahamas is limited by hurricanes in exposed regions, cold winters in the northern Bahamas and by turbid, hypersaline waters on the leeward bank margins.

Status of coral reefs prior to 2005: Prior to 2005, live coral cover in the Bahamas was highly variable between sites, with cover ranging between 1% at Lindsay Reef at 4 m depth to 47% at Strip Reef at 10 m.

Impacts of Coral Bleaching in 2005: Reef Check conducted one survey at Turtle Rocks in August 2005 during the coral bleaching episode. This survey determined that live coral cover was 14%; 17% of coral colonies were affected by bleaching; and bleached colonies exhibited bleaching over 25-50% of their surface. No recently killed coral was recorded during the survey and a subsequent survey conducted in August 2006 recorded live hard coral cover of 18%, indicating that the 2005 bleaching event caused little or no coral mortality in the Bahamas.

Bermuda

Geographic Distribution and Extent of Coral Reefs: Bermuda is an isolated island chain 920 km off the coast of North Carolina on the Bermuda Platform. Together with the Challenger and Argus Banks, they occupy about 900 km². The fringing, bank-barrier and lagoonal patch reefs form the most northerly coral reef system in the Atlantic and are supported by warm water eddies from the nearby Gulf Stream. Coral diversity is, however, limited by cool winters.

Status of coral reefs prior to 2005: There has been little change in these coral reefs, which are the most northerly reefs of the region (Latitude 32°20'N), during the 10 years to 2005. Coral cover remained at 20% around the rim, 10-15% on lagoon patch reefs, and 45-50% on terrace reefs. There are healthy herbivorous fish populations, and the reefs escaped serious impacts caused by coral bleaching that damaged reefs to the south in 2005. A comparison with the first surveys 25 years ago illustrates the stability: hard coral cover on the terraces - 52.4% in 1981 vs 54.0% in 2005; and 22.5% in 1981 on outer rim coral-algal reefs vs 24% in 2005. Much of the stability on Bermudan reefs could be the result of a predominance of slow growing massive growth forms (*Diploria*, *Montastraea* and *Porites* species) and few branching and bleaching sensitive corals like *Acropora*.

Impacts of Coral Bleaching in 2005: Some coral bleaching was observed on Bermudan reefs in 1988, 1991, 1992, 1995, 1998 and 2003, however, only the 1988 and 2003 events were recorded in detail. In 2005, seawater temperatures peaked at 30.3°C in mid to late August at most locations, except at 10-15 m depth on the terrace reef sites, which peaked at 28.7°C in early September. All sites cooled with the passage of tropical storm Philippe. Thus, seawater temperatures during 2005 were not unusual compared with previous summers and no widespread bleaching or disease of corals was observed. Hard coral cover was 22.7% in 2005; the same as 2004 and a slight increase on the 14 year mean (20.8%). Black-band disease and white plague on *Diploria*, *Montastraea* and *Porites astreoides* are the most common diseases in Bermuda, and occur mostly on the outer rim and lagoonal patch reefs. Yellow blotch disease is also relatively common in *Montastraea franksii*.

Impacts of Hurricanes in 2005: In 2005, there were 3 tropical storms ('Franklin', 'Harvey' and 'Philippe') and 2 hurricanes ('Nate' and 'Wilma') near Bermuda. However, peak wind speeds did not exceed 90 km/h (i.e. generally less than regular winter storms). The major effects of these storms were to temporarily lower seawater temperatures by 1-2°C, with no significant damage to the coral reefs.

Cayman Islands

Geographic Distribution and Extent of Coral Reefs: The Cayman Islands contain 3 individual islands (Grand Cayman, Little Cayman and Cayman Brac) on the Cayman Ridge, which extends from southeast Cuba to the Bay of Honduras. They are flanked to the south by the 6000 m deep Cayman Trench. These low-lying limestone platforms with narrow island shelves support prolific coral reefs. There is little obvious human impact on the coral reefs surrounding Little Cayman, which is the smallest and least developed of the 3 Cayman Islands. Thus, Little Cayman could provide a reference site for coral research in the central Caribbean.

Status of coral reefs prior to 2005: On Grand Cayman, mean coral cover declined from 25.7% in 1997 to 15.4% in 2001, probably because of bleaching events, lethal coral diseases and algal overgrowth. Increases in the abundance of algae in coastal waters near the more populated parts of the islands appear to have resulted from nutrient pollution leaching from resorts and residential areas. Atlantic and Gulf Rapid Reef Assessment (AGRRA) surveys of 18 fore-reef sites around Little Cayman showed a major loss in coral cover of nearly 40% (declining from 26.3% to 15.8%) from 1999 to 2004. There has been no further decline since.

The reefs continue to support relatively diverse and abundant fish assemblages. Previous conservation regulations did not prevent over-fishing of high value species such as conch, lobster and grouper, and there was little protection of grouper spawning grounds and turtle nesting sites from coastal development. The relevant regulations have been recently amended.

Impacts of Coral Bleaching in 2005: In August 2005, corals at all sites around Little Cayman showed signs of bleaching and there were also colonies infected with coral disease at 6 of the 8 study sites. Coral cover ranged between 9% and 22% (avg. 12.9%), and the amount of bleached coral in 2005 was the highest ever recorded. *Dichocoenia stoksii* was totally bleached, and partial bleaching was recorded in most colonies of *Montastraea faveolata*, *M. annularis*, *M. franksii*, *Agaricia agaricites*, *Siderastrea siderea*, *Diploria strigosa*, and *Porites porites*. Live hard coral cover did not decline in 2006, indicating that most corals had recovered from bleaching stress and there was little coral mortality.

Five coral genera, *Montastraea*, *Agaricia*, *Diploria*, *Porites*, and *Siderastrea* dominate Cayman Island reefs, and comprise more than 90% of all corals found. Between 1999 and 2005, *Montastraea* decreased in density by 30% (from 46% to 32%), *Porites* increased by 50% (11.8% to 17.7%) and *Agaricia* rose by 15% (22% to 25.4%). Average mortality rose from 29.0% to 42.7% for *Montastraea*, which was much greater than the average for all genera over those years (23.4% to 28.3%). The main cause of *Montastraea* loss appears to be white plague disease; this is serious because the massive frame-builder *Montastraea* usually dominates fore-reef spur and groove formations in the Caribbean. Despite these declines, coral recruitment on Little Cayman reefs has not declined, which demonstrates that these reefs have the capacity to recover; offering some hope for the future.

Impacts of Hurricanes in 2005: Several hurricanes passed within 150 km of Little Cayman in the last 40 years: 'Allen' 1980; 'Gilbert' 1988; 'Mitch' 1998; and 'Ivan' 2004. Hurricane 'Dennis' in 2005 passed between Little Cayman and Cuba and caused minimal damage. However, Hurricane 'Ivan' passed south of Little Cayman and made a direct landfall on Grand Cayman

on 12 September, 2004. Large masses of sand piled up on back-reef corals and in lagoons on the south side of Little Cayman. By November 2004, there was little obvious damage on the fore-reef slopes.

Cuba

Geographic Distribution and Extent of Coral Reefs: The main island of Cuba, the Isle of Youth and 4195 cays and islets are distributed over 110,860 km². The islands are at the entrance of the Gulf of Mexico, between the Atlantic Ocean and the Caribbean Sea. Numerous fringing and bank-barrier reefs border more than 98% of Cuba's 3200 km shelf margin, although more than 50% are separated from the mainland by cays or by broad, shallow lagoons with many patch reefs. This separation has provided the outer reefs with protection from anthropogenic influences, except for fishing and, in some places, tourist diving. Reef crests in Cuba tend to be more abundant at the edge of the 4 broad sections of the Cuban shelf: the Golfo de Guanahacabibes (Northwest Cuba); Archipiélago Sabana-Camagüey (central north); Golfo de Ana María-Guacanayabo (southeast); and Golfo de Batabanó (southwest). The narrow shelf of the Northeast also has well developed reef crests. Inshore patch reefs are dispersed on the northwest (Golfo of Guanahacabibes), southwest (Golfo de Batabanó) and southeast (Golfo de Ana María-Guacanayabo) where there are unique reefs on muddy substrata. There are 2 barrier reefs: Archipiélago Los Colorados (NW Cuba); and Archipiélago Jardines de la Reina.

Status of coral reefs prior to 2005: Live coral cover averaged 21% on Cuban reef crests and shallow reefs and 18% on fore-reefs. The corals have been stressed by organic and chemical pollution around populated areas, diseases, the *Diadema* die-off and resultant competition with algae, and some earlier bleaching. The reefs were recovering from these stresses until 2005, when bleaching and hurricanes resulted in coral mortality.

Impacts of Coral Bleaching in 2005: In summer 2005, coral bleaching was widespread and intense. Assessments conducted by the Early Warning Coral Reef Volunteer Monitoring Network showed that coral bleaching around Cuba varied from 1-10% to 75-100% of colonies, predominantly between categories 50-75% and 75-100% (at 89% of reported sites). Only one site, Punta Francés (SW of Isla de la Juventud), suffered lower intensity bleaching (1-30%). Most anecdotal reports refer to a high degree of recovery by May 2006.

Impacts of Coral Bleaching in 2006: Coral bleaching in 2006 was widespread but with varying intensities, increasing after mid-September. The volunteer monitoring network reported that coral bleaching did not exceed 10% and was generally not higher than 5%. María la Gorda was an exception with 10-30% colonies bleached at 20-25 m depth, but much less in shallower areas. Warming increased in mid-September, and moderate bleaching (10-30%) was recorded at Havana City and Jardines de la Reina Archipelago, and intense bleaching (75-100%) at Punta Francés (SW Isla de la Juventud). Bleaching was low in the Sabana-Camagüey Archipelago and Bahía de Cochinos. No information is available from Santiago de Cuba and Granma provinces, to the east.

Impacts of Hurricanes in 2005: Hurricane Denis, which made landfall in July, 2005 near Punta del Inglés, caused only minor damage at Cabo Cruz and Pilón (Nacional Park Desembarco del Granma, south-eastern Cuba), despite wind velocities reaching 310 km/h.

The reef was not exposed to the direct force of the wind and waves and only a few colonies of *Acropora palmata* (<10%) were fragmented. However, at Pilón (to the east), the impact was much greater because of its windward position. Many sponges and gorgonians were damaged, corals suffered fewer losses and sand was removed from the beaches.

In October, 2005, Hurricane Wilma produced wind velocities of 70-90 km/h, with gusts to 110-120 km/h, and 4-5 m waves at La Bajada-Uvero Quemado-María la Gorda (Ensenada de Corrientes, western Cuba). Many hard coral colonies and gorgonians in shallow water (<6 m) were removed. Damage was significantly less in the spur and groove zone (10-12 m), with only a few hard coral colonies fragmented or overturned. The sea-urchin *Diadema antillarum* disappeared in places where it had been abundant. Approximately 10-15% of hard coral colonies were bleached after the hurricane.

Wilma caused damage to coral reefs near Havana City, down to depths of 15 m; many sponges and gorgonians were deposited onshore and a few *Acropora palmata* colonies were overturned or fragmented. Massive corals were less affected; but the recovering *Diadema* population was devastated. However, seagrass beds and mangroves behind reef crests suffered only minor damage.

Socioeconomic impacts and management responses: In spite of current economical constraints, Cuba is still devoting much effort to coral reef assessment, research and monitoring, through different research projects and scientific-technical services. Since 1995, tertiary treatment for sewage generated by all tourist developments has been compulsory. These requirements are implemented and enforced through recently established EIA and licensing processes (Resolution No. 168/95 of Environmental Impact Assessment). Recent water quality assessments show that pollution from tourist resorts is negligible. In addition, destruction of coastal areas has been prohibited through the establishment Decree-Law 212 (year 2000) of Coastal Zone Management. Since then, there has been no additional anthropogenic destruction of the largely undisturbed mangroves.

Dominican Republic

Geographic Distribution and Extent of Coral Reefs: The Dominican Republic has 1576 km of coast including the islands of Saona, Catalina, Beata and the Cayos Siete Hermanos, with coral reefs along 166 km and mangroves along 377 km. The longest reef (64.2 km) is to the northwest of Montecristi. Most of these are fringing reefs, but there are also 2 barrier reefs, numerous patch reefs, and 4 large offshore banks. On the east and northwest coasts, there are broad coastal shallow platforms with barrier reefs. In most other places, high turbidity prevents reefs from forming.

Status of coral reefs prior to 2005: CARICOMP data show that coral cover rose from 8.2% in 2000 to 11.5% in 2001 and Reef Check surveys showed mean coral cover of 19.4% at Bayahibe in 2004.

Impacts of Coral Bleaching in 2005: Reef Check surveys recorded significant bleaching at all sites surveyed during September/October 2005. Bleaching affected as much as 68% of live corals, with the majority of colonies being entirely bleached. The average mortality was 11% across all sites surveyed, but there was great variation between sites with mortality ranging

between 0% and 38%. Significant bleaching also occurred between late May and the end of August 2006, with bleaching affecting between 66% and 85% of living coral cover and individual colonies exhibiting bleaching over 50-95% of their surface areas.

Jamaica

Geographic Distribution and Extent of Coral Reefs: Jamaica is the 3rd largest Caribbean island; 230 km long by 80 km wide with 891 km of coastline and a coral reef area of 1240 km². Well developed fringing reefs occur along most of the north and east coasts, while patchy fringing reefs grow on the broader shelf of the south coast. Reefs and corals also grow on the neighboring banks of the Pedro Cays, 70 km to the south, and the Morant Cays, 50 km to the southwest.

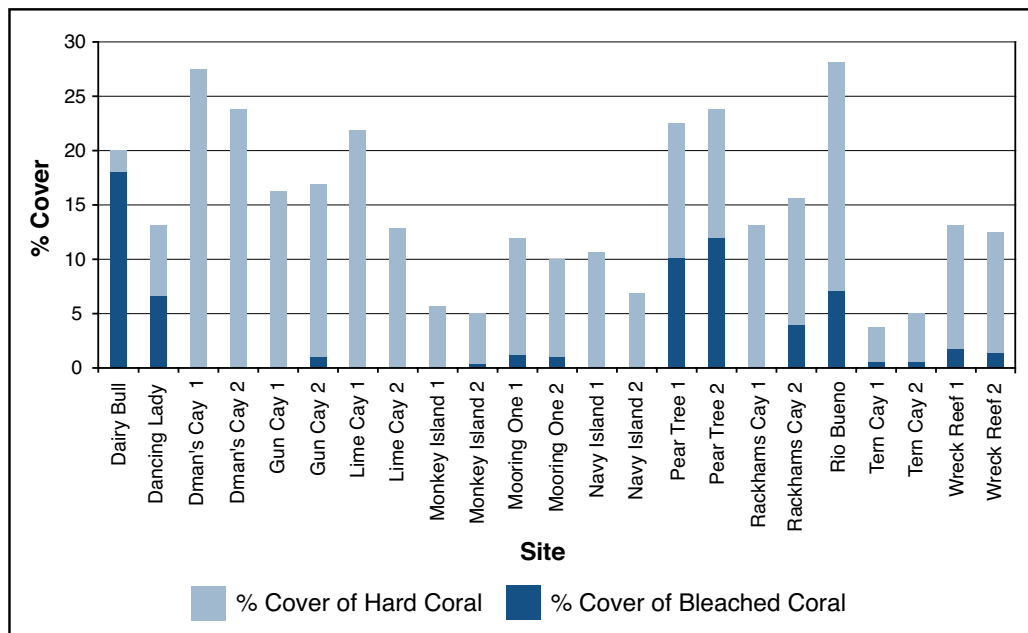
Status of coral reefs prior to 2005: Hard coral cover declined from 50% in the 1970s to less than 5% by the early 1990s as a result of hurricanes, *Diadema* die-off, coral diseases, and over-fishing. Coral cover has risen to 10-15% recently, with some sites having coral cover of 34-46%. Fish populations in Jamaica have been declining for decades because of poor fishing practices. Reef Check surveys at 35 sites between 2001 and 2006 reported an average density of 9.8 fish per 100 m².

Impacts of Coral Bleaching in 2005: Between August and October 2005, there were prolonged high sea surface temperatures around Jamaica and nearby countries, with 5 to 6 weeks of greater than normal temperatures, which resulted in widespread bleaching. This was first observed on the north coast from late August to early September and on the south coast in late September to early October. Corals started recovering as early as February/March when sea temperatures began to cool.

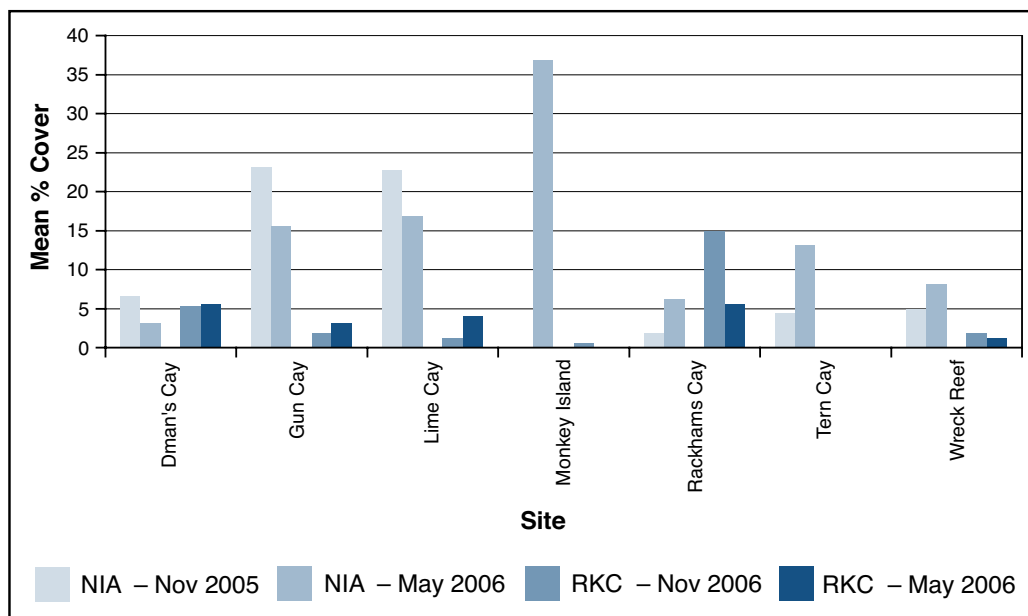
Bleaching was assessed 26 times at 16 sites. Variation in the proportion of corals bleached ranged from 10% to 95%, with *Montastraea annularis*, *M. faveolata*, *M. cavernosa*, *Siderastrea siderea*, *Diploria strigosa*, *Agaricia* spp., *Millepora complanata* and *Porites porites* being most commonly affected. Within five months, about 50% of the bleached corals had recovered. There were however, increases in recently killed coral and fleshy algae, which usually indicate nutrient pollution.

In September 2006, black-band and white plague diseases were noted in the Port Royal Cays, especially Lime Cay and South-east Cay. White plague has been the most prevalent disease since January 2006, affecting the massive corals *Siderastrea*, *Montastraea*, and *Diploria* species.

Impacts of Hurricanes in 2005: Major hurricanes that have damaged Jamaica's reefs include 'Allen' in 1980, 'Gilbert' in 1988 and 'Ivan' in 2004. The hurricanes in 2004 and 2005 passed to the south of Jamaica causing most damage to south coast reefs. Hurricane Ivan passed parallel to the south coast in September 2004 causing damage to Port Royal and Portland Bight Cays, with large numbers of fractured and killed branching corals in shallow water (2-8 m). Other nearby corals were turned over, relocated, abraded and bleached. Some survived virtually undamaged or with only partial mortality. The lesions caused during the hurricane were quickly being overgrown by fast growing opportunistic algae; however, by February, 2005,



Live hard coral cover (light bars) ranged from 3.1% to 28.1% (average 13.4%). At some sites on Lime Cay, Drunkenman's Cay and Dairy Bull, more than 80% of the coral community bleached (dark bars).



Comparison of the percent cover of nutrient indicating algae (NIA) and recently killed coral (RKC) recorded during surveys in November 2005 and May 2006.

some of the corals displayed evidence of recovery and growth. In 2005, Hurricanes ‘Dennis’, ‘Emily’ and ‘Wilma’ passed close to the island bringing heavy rainfall and wind. Although the island was not affected directly by either of these systems, the southern parishes and the western town of Negril were hit by storm surge that toppled some corals.

Mangroves and seagrasses: The government, through the National Environment and Planning Agency (NEPA), has embarked on a process that will eventually lead to a no net loss policy for mangroves and seagrasses. Where development will result in loss or destruction, it is required that there is relocation/rehabilitation of an area roughly 120% the size that is lost or damaged.

Socioeconomic impacts and management responses: It is expected that the impacts of the damage associated with these events will ripple throughout the fabric of the socioeconomic environment in Jamaica as they have undoubtedly contributed to the continued decline in the landed fisheries resources of the island. Management responses have included cancelling the bird shooting season after hurricane Ivan to allow time for populations to recover (inclusive of mangrove areas).

NEPA has implemented a stricter permit and licensing system for activities that may damage coral reefs, and also ensured that assessments are conducted to feed into annual reports on resource status, with recommendations for management and improvement. A defined government policy on wetlands (inclusive of coral reefs, mangroves and seagrasses) is being planned.

The Government has implemented programs to increase the number of monitoring sites and the frequency of monitoring undertaken. This is facilitated by the University of the West Indies and the Jamaica Coral Reef Monitoring Network.

In an effort to improve conservation efforts by the Government and the general public, the importance of all coastal ecosystems is continually being emphasized by demonstrating the economic losses that occur as a direct result of ecosystem degradation.

Turks and Caicos Islands

Geographic Distribution and Extent of Coral Reefs: There are 8 low-lying limestone islands and 40 small sand cays distributed over 1736 km² in the Turks and Caicos, which is on an extension of the southeastern Bahamas Platform. All the islands and cays are fringed by narrow, discontinuous, shelf-edge reefs dominated by corals, algae and gorgonians growing down to 40 m, on hard substrata.

Status of coral reefs prior to 2005: Reef condition across the islands was quite similar, although human pressures from fishing, boat grounding, diving/snorkeling, sediments and nutrient flows from coastal development, varied between islands. Live coral cover on Providenciales ranged from 6–36%, with extremely low macro-algal cover. The near shore patch reefs had many isolated coral heads of *Montastraea* and *Diploria*, and a high cover of gorgonians. *Montastraea*, *Siderastrea* and *Porites* were the dominant corals on South Caicos. The cover of macro-algae at South Caicos was generally higher and this is probably related to

greater fishing activity and localized eutrophication. The Grand Turk reefs were generally in good condition, with 24% average coral cover (range 17-33%) and high coral diversity that was dominated by *Montastraea annularis*, *M. cavernosa*, *Siderastrea siderea* and *Agaricia agaricites*, with many gorgonians and low algal cover (1-20%). However, the average coral cover at 5 major dive sites decreased from 32.4% in 1995 to 21.9% in 2004.

There were active domestic and export fisheries, especially for queen conch (*Strombus gigas*), spiny lobster (*Panulirus argus*), grouper, hogfish and snappers. Herbivores, such as parrotfish and surgeonfish, are usually not kept. Most fishing is done with hand lines but there were a few traps. Generally, fishing pressure was relatively low and fish communities were relatively intact on both the Turks and Caicos Banks, with potential yields assessed by AGRRA of 70–140 kg per km² with an average fish density of 2-14 fish per 100 m² for selected families (Pomacanthidae, Cheatodontidae, Balistidae, Acanthuridae, Haemulidae, Lutjanidae, Serranidae and Scaridae). Fishermen have reported little change in the past 5 years.

Impacts of Coral Bleaching in 2005: The first coral bleaching occurred on South Caicos between September and December 2005. Of 166 coral colonies at The Warhead, The Fishbowl and Tuckers Reefs, only 3 colonies (1 *Montastraea annularis* and 2 *Agaricia agaricites*) were completely bleached, and 87 colonies showed partial bleaching. In shallow water (<6 m), bleaching was seen in colonies of *Acropora cervicornis*, *M. annularis*, *Stephanocoenia intersepta*, *A. agaricites*, *Montastraea cavernosa* and *Diploria labyrinthiformis*. At 10 m, colonies of *M. annularis*, *A. agaricites*, *Porites porites*, and *Porites astreoides* were bleached, while at 15 m there was bleaching in colonies of *M. annularis*, *A. agaricites* and *Siderastrea siderea*.

Coral colonies appeared to be recovering in December 2006, with little evidence of coral mortality. The Department for Environmental and Coastal Resources initiated coral bleaching surveys to follow progress as some black-band disease was evident on South Caicos, similar to previous years.

CONCLUSIONS AND RECOMMENDATIONS

The increased frequency and incidence of intense hurricanes coupled with abnormal rising sea temperatures are now common annual dilemmas facing the Node countries. Coastal ecosystems are now stressed more frequently and as such have less time to recover before the next catastrophe.

All countries continue to face similar problems of infrastructure related to funding and human resources. In the face of these difficulties, they are still committed to achieving environmental health by implementing monitoring and conservation exercises. All are still trying to achieve a balance between conservation and economic growth and have employed several measures to achieve this, such as integrated coastal zone management. The process is still being hampered in some cases by outdated laws and fines, and because some governments are still sacrificing the environment in their bid to achieve economic growth. To halt the continued degradation of the region's natural resources, outdated legislation and fines need to be revised. More monitoring is also required, but to achieve this, the lack of trained personnel available to conduct assessments needs to be addressed.

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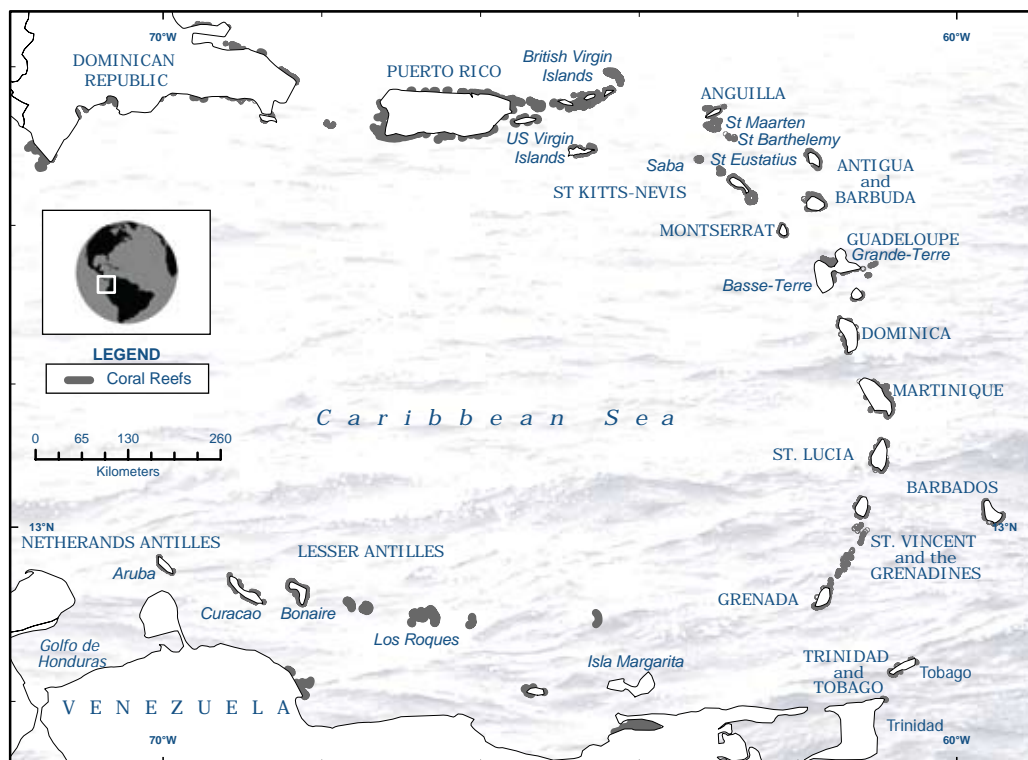
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8. STATUS OF CORAL REEFS OF THE LESSER ANTILLES AFTER THE 2005 CORAL BLEACHING EVENT

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SUMMARY

- During summer 2005, a persistent 'HotSpot' surrounded these islands;
- Coral bleaching and mortality was probably the most severe ever recorded in the Lesser Antilles and was the most extreme for the wider Caribbean during 2005;
- The most severe bleaching event ever recorded at Barbados occurred during September and October 2005, and affected all coral species at all depths, and all reef types and habitats;
- There was between 25% and 52% mortality of corals in the French West Indies, especially at Guadeloupe and Martinique. Bleaching affected most coral species and resulted in reduced larval recruitment in the following 2 seasons. However, there appears to be no effects on fish populations;
- There was extensive bleaching (80%) on the northern Netherlands Antilles islands of St. Maarten, Saba, and St. Eustatius in August 2005; but only minor bleaching and minimal mortality on the southern islands of Bonaire and Curaçao;
- On the island of Tobago, most species bleached, with 66% average cover of bleached coral. Bleaching in *Montastraea annularis* was highly variable; there was 73% bleaching in one stand, but only 6% in another, on Buccoo Reef;
- No hurricanes passed through this region in 2005; this partially explains the severity of bleaching as there were no strong winds to lower seawater temperatures;
- These islands are highly dependent on their coral reefs, thus there is an urgent need for appropriate management responses as sea temperatures are predicted to rise further in future.



Map of the Lesser Antilles region.

The French West Indies

INTRODUCTION

The French West Indies (FWI) in the Lesser Antilles lie between 14°20' and 18°00' N and consist of the islands of Martinique, the Guadeloupe Archipelago (with Guadeloupe, La Désirade, Marie-Galante and Les Saintes islands), St. Barthélemy, and the French part of St. Martin/St. Marteen. The population in these islands was 834,000 people in 2004, including about 2500 registered fishers.

Guadeloupe and Martinique are volcanic and mountainous islands, situated roughly in the centre of the West Indies and surrounded by a narrow island shelf that receives high levels of volcanic sediments. Corals grow on the rocky surfaces and form fringing reefs on the eastern sides. These reefs are especially important for tourism; 665,000 tourists visited Guadeloupe in 2005 and 381,000 visited Martinique in 2004. Thus tourism is a major economic contributor in the FWI with hotel capacity of Guadeloupe and Martinique exceeding 13,000 rooms and additional accommodation available in small-scale rural cottages. The most common marine tourist activities are glass-bottom boat tours, kayaking, water skiing, surfing, sailboat rentals, sport fishing and particularly scuba diving. There are 40 scuba diving clubs in Guadeloupe and a similar number in Martinique, with diving focused on the Caribbean (leeward) coasts. For example, about 100,000 divers visit the Îlets Pigeon in Guadeloupe each year.

A mix of fringing and barrier reefs grow on the narrow shelves surrounding Guadeloupe and Martinique. These are similar to reefs growing around high islands in the Eastern Caribbean States with better development on the windward coasts of the islands, but greater biodiversity on the protected leeward coasts. There are 4 marine reserves: 2 in Guadeloupe; 1 each in St. Barthélemy and St. Martin; and 9 no-take zones in Guadeloupe and Martinique.

Saint-Barthélemy and Saint-Martin are the northern-most islands in the FWI, situated on a shallow, sediment covered shoal. Saint-Barthélemy is surrounded by numerous small islands, and Saint-Martin/Sint-Maarten is under French and Dutch control. There are poorly developed fringing reefs and extensive seagrass beds around both islands, and large areas of mangroves have been destroyed by land reclamation.

STATUS OF CORAL REEFS PRIOR TO 2005

There is very clear evidence of coastal ecosystem degradation throughout the FWI, which has affected coral reefs, seagrass beds and mangroves. Long-term monitoring since 1999 has shown that the coral communities of Guadeloupe and Martinique have been degraded, particularly during the last 7 years, confirming qualitative observations since the early 1980s. High rainfall, deforestation for agriculture, poorly managed coastal development and mangrove clearing have resulted in excessive sediments and nutrients flowing into coastal waters, especially into enclosed bays and lagoons. Elevated nutrient loads from overuse of fertilizers and poor wastewater treatment have fueled the proliferation of algae, particularly *Sargassum* and *Turbinaria* on the exposed outer slopes on the Atlantic coasts, and *Dictyota* on more sheltered areas in lagoons and reefs on the Caribbean coasts. *Turbinaria* and *Sargassum* are highly resistant to waves generated by hurricanes, whereas *Dictyota* is removed by each passing hurricane, although it recolonizes reefs rapidly after storms. Chronic over-fishing has reduced fish stocks, particularly herbivorous fish that control algal communities.

Previous coral bleaching from elevated sea surface temperatures (SST) during El Niño years in 1984 and 1987 was relatively minor. The first significant bleaching occurred in September and October 1998, when the SSTs exceeded 29°C for several weeks. There was extensive bleaching of hard corals, actinarians, zoantharians and gorgonians. Although these reefs suffered some mortality among certain corals, the effects of bleaching in the FWI were relatively small compared with other regions in the Caribbean. Bleaching occurred again in 1999 in Guadeloupe, but the effects of bleaching were obscured by damage caused by Hurricane Lenny. FWI reefs show chronic but minor bleaching almost every year in September when SSTs exceed 29°C for a short period.

The waves generated by hurricanes limit coral reef growth in the Lesser Antilles, and severe hurricanes cause serious damage to coasts every 10 years on average. Direct physical damage to coral reefs occurs to 15 m depth and recovery can take years to decades. Hurricanes are usually accompanied by torrential rains that wash massive quantities of sediments and nutrients onto nearshore reefs, resulting in short-lived algal blooms. Since 1989, there have been 4 hurricanes that have directly damaged the FWI: Hurricane Hugo (1989) hit Guadeloupe; and Saint-Barthélemy and Saint-Martin were damaged by Hurricanes Luis and Marilyn in 1995, and Lenny in 1999, which also caused damage to Guadeloupe.

Guadeloupe: The first signs of reef decline were evident in the 1980s, and by 2000, satellite remote sensing showed that only 15-20% of the marine habitats in Guadeloupe still had healthy coral communities. Coral cover varied from 15-22% on reef flats; and 24-26% on outer slopes before 2005. The proportion of coral colonies showing disease ranged from 23-33%, with the average surface area of dead tissue ranging from 27-32%. Algal turf was the dominant component of the benthic community, but the greatest changes were in the cover of brown macro-algae, which were influenced by nutrient concentrations, seasonal temperature changes and wave action. The increase in macro-algae was also favored by the decline in sea urchin populations during the early 1980s and over-fishing of herbivorous fish.

The reefs of Guadeloupe were not severely damaged by previous coral bleaching, although 56% of corals bleached in 1998, with up to 80% of the surface area of colonies being pale. There was, however, little mortality except among colonies of *Diploria labyrinthiformis*, which suffered 80% mortality. Another bleaching episode that was confined to the reefs of Guadeloupe occurred in September 1999, affecting almost 50% of corals. Subsequent mortality was negligible because the passage of Hurricane Lenny in November 1999 cooled the waters and allowed corals to recover.

In 1989, Hurricane Hugo destroyed branching corals (*Acropora palmata*, *A. cervicornis*, *Madracis mirabilis*) on the outer reef slopes down to depths of 15 m. The *A. palmata* stands, which were prominent on the outer reef slopes, have not recovered but *Madracis mirabilis* has quickly recolonized the area. Hurricanes Luis, Marilyn and Lenny damaged Guadeloupe's coral reefs more severely than Hugo, mainly because large waves up to 13 m high destroyed corals, sponges and gorgonians down to 25 m depth. This damage was compounded by torrential rains and extensive soil erosion. The high diving pressure on these reefs causes additional damage, particularly from inexperienced divers, especially on the Ilets Pigeon, which receives between 80-100,000 divers annually.

Surveys at Guadeloupe in 2000 recorded 228 fish species in 59 families, with the average fish density between 119 and 550 fish per 600 m². The highest numbers were in the protected area of Pigeon Island. The fish biomass in Guadeloupe and the other islands was 368 to 1893 kg. ha⁻¹. In 2004, the average number of fish species in 600 m² areas was 45 and the average fish biomass in Guadeloupe was 807 kg. ha⁻¹, indicating that fish communities have not changed significantly in recent years. However, fish stocks around all the islands are over-exploited and large fish (groupers, snappers, parrotfish) are rarely seen. Most fishing is artisanal with 1200 registered fishers, working from 947 fishing boats that are generally small (6-8 m long) and operate in inshore waters. Only 10 boats are equipped to operate offshore. There are however, about 1000 unregistered fishers who fish regularly. About 40,000 Caribbean traps are used, with many of these traps being 'lost' after each hurricane. However, those traps with wire or plastic netting continue to catch fish long after they are lost.

Martinique: Coral cover in 2004 varied between 32% and 40% on various reefs. The dominant cover type was algal turf followed by brown macro-algae, indicating that nutrient pollution from the land is affecting the marine environment. The increase in brown macro-algal cover is a major factor contributing to the deterioration of the reefs. The proliferation of macro-algae was first noticed on the Atlantic coast in the early 1980s, coinciding with the mass mortality of the herbivorous sea urchin *Diadema antillarum*. Since 1984, macro-algae, particularly *Sargassum*, have become abundant along the Caribbean coast, probably because

of eutrophication resulting from urban and industrial wastes from Fort-de-France Bay and sediment from agriculture. In the early 1980s, Fort-de-France Bay had the highest coral diversity in a variety of different habitats (reefs, seagrass beds, shoals, rocky shores). However, increasing pollution is threatening these ecosystems and those in the nearby Baie du Marin.

Like Guadeloupe, the reefs of Martinique were not severely affected by previous bleaching events. In 1998, 59% of coral colonies bleached, with an average of 69% of the surface area of colonies being bleached. However, there was little subsequent mortality and recovery was reasonably rapid. There was minimal bleaching in 2003 and 2004, but no significant mortality.

Hurricanes have caused significant damage to the coral reefs of Martinique; Hurricanes David in 1978 and Allen in 1980 damaged *Acropora palmata* and *A. cervicornis* communities, especially in the Sainte-Luce region. Although there has been no major hurricane damage since then, these reefs have not recovered completely.

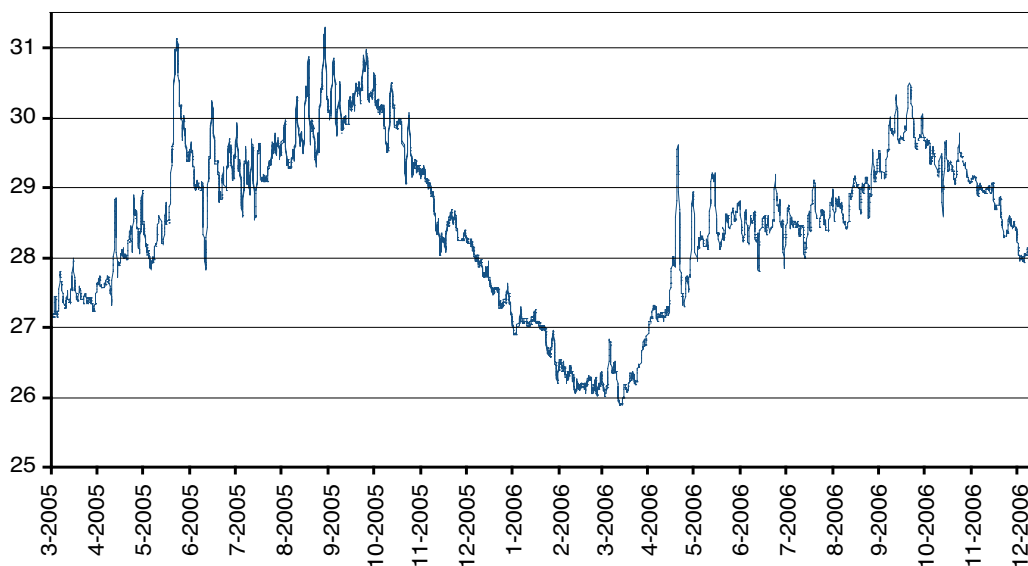
Fishing in Martinique is also primarily artisanal. At present, there are about 1300 registered fishers who use traps and concentrate their fishing effort on inshore reefs. There are many more unregistered fishers, making the total fishing population closer to 2500. The catch of pelagic species has risen with the introduction of anchored fish aggregating devices. There was a major fish kill in September 1998, which affected all trophic levels on the Atlantic coast of Martinique. However, there were no obvious changes in the structure of the reef fish community. Surveys in 2004, showed an average of 46 fish species in 600 m² areas and an average fish biomass of 788 kg.ha⁻¹, indicating that no significant changes in fish communities have occurred recently.

Saint-Martin and Saint-Barthélemy: Coral cover varied in 2004 between 20% and 26%. Algal turf was the most abundant cover type on the reefs of Saint-Barthélemy. Brown macro-algae were also abundant, indicating that nutrient pollution was affecting these reefs. The reefs of Saint-Martin and Saint-Barthélemy have been colonized by *Dictyota* and *Lobophora*, which out-compete corals and other benthic invertebrates for space. Hurricane Luis caused some damage to the coral reefs of Saint-Martin and Saint-Barthélemy, but the most significant impact was caused by the re-suspension of very fine sediments from the shallow continental shelf. These sediments remained in suspension for several months and smothered many organisms. Re-suspension of sediments is probably a reason for the limited development of coral reefs on these islands.

In 2004, the average number of fish species in 600 m² areas was 48 and the average fish biomass was 751 kg.ha⁻¹. There have been no apparent changes in fish communities in recent years, although seasonal variations of fish biomass were noted on the reefs of Saint-Barthélemy.

THE 2005 TEMPERATURE ANOMALY IN THE FRENCH WEST INDIES

Generally, Caribbean reef corals tolerate a maximum sea water temperature of 29°C; any increase above this for a long period will stress corals and induce bleaching. The severity of bleaching is linked to the magnitude of the temperature increase and its duration. There is usually some minor bleaching every September when sea temperatures reach their annual maximum.

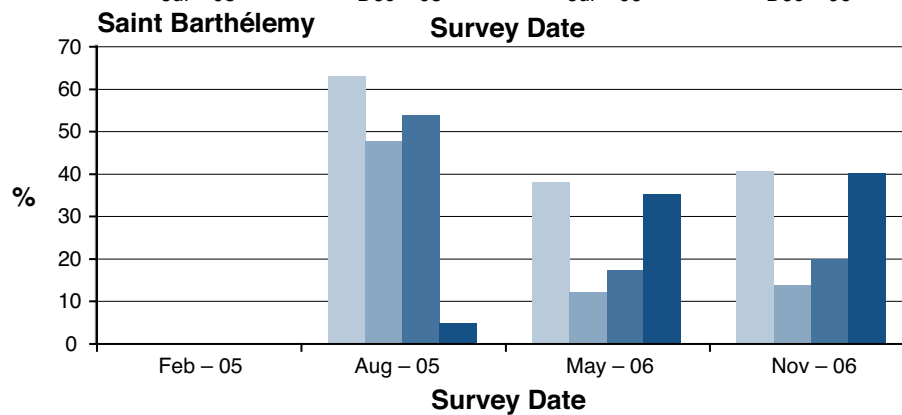
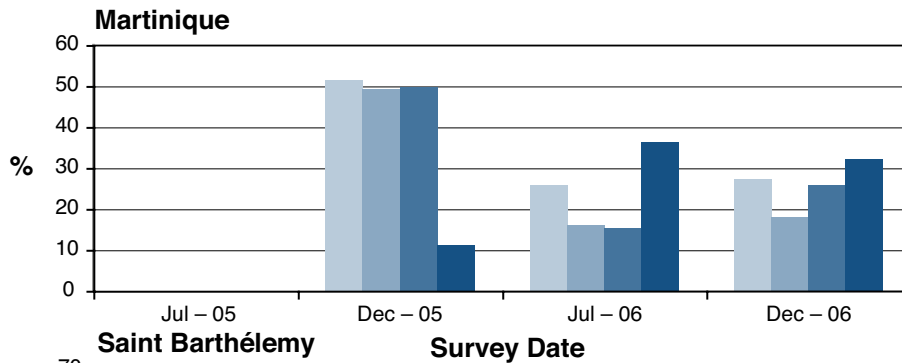
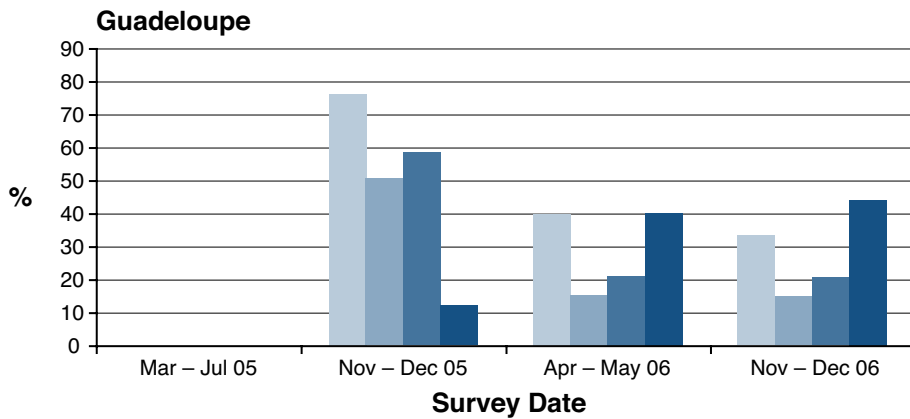


This figure daily sea temperatures in Guadeloupe from March 2005 to December 2006, with consistent temperatures over the 29°C ‘bleaching threshold’ for almost 6 months in 2005, reaching a maximum of 32°C in September, and then for a short period in 2006. (24 h moving average).

EFFECTS OF THE 2005 BLEACHING EVENT

Guadeloupe: Severe coral bleaching developed in August after sea temperatures exceeded 29°C between May and November. Surveys in December 2005, showed that bleaching had affected 76% of all coral species in the community; 51% of all colonies; an average of 58% of the surface area of affected colonies; and a 12% loss of coral cover. The density of coral recruits during this period was the lowest recorded, declining from a mean of 23 recruits per 10 m² prior to 2005 to 10 per 10 m² in December 2005. There was also a significant drop in the number of coral species and colonies recruiting in 2006.

Few corals recovered in 2006, particularly in shallow areas, and there was delayed mortality throughout the year despite normal sea temperatures at most reef sites. Some of this mortality was the result of coral diseases, but most was because of the slow death of bleached colonies that had not recovered their zooxanthellae symbionts. At the end of 2006, bleaching still affected 33% of coral species, 15% of all colonies, and an average of 21% of the cover of coral. The condition of surviving colonies also deteriorated in 2006, with the number of coral species showing coral disease increasing from 60% to 71%, while disease in colonies rose from 33% to 39%. The average colony surface area affected by tissue necrosis varied from 32%-49%. The delayed mortality resulted in a decline of live coral cover on the outer reef slopes, from between 44% and 25% cover before bleaching, to 14% after. Simultaneously, the mean cover of algae rose by 15% on the outer reef slopes.



The effects of increased sea temperatures on the coral reefs of the French West Indies are presented in these 3 figures. There was no apparent bleaching by July 2005; but between August and December, there was clear evidence of a major bleaching event with about half of all corals bleached, but few signs of mortality. However, by mid-2006, 30% to 40% of the coral cover had died, and more than 10% of the remaining corals were bleached.

Observations in June 2007 showed that many corals remained pale or partially bleached and had not fully recovered their stock of zooxanthellae, despite normal seawater temperatures. The three-dimensional structure of the reefs was apparently not affected by the bleaching; for example, in 2004, the average number of fish species per 600 m² was 45 and the average fish biomass was 807 kg.ha⁻¹ and by the end of 2006, comparable measures were 48 species and 994 kg.ha⁻¹.

Martinique: Bleaching started in August 2005 and the first surveys in December showed that bleaching affected 51% of coral species, 49% of all coral colonies, and an average of 50% of the surface area of each colony. Coral mortality was moderate in December with a loss of 11% in coral cover. The number of coral recruits decreased from an average of 49 recruits per 10 m² in July 2005 to 28 recruits per 10 m² in December 2005, even though coral recruitment is usually greater in December. Juvenile recruitment was still low in 2006 (32 recruits per 10 m²).

Bleaching persisted during 2006 and by the end of the year, 27% of all coral species showed signs of bleaching and 18% of coral colonies were affected. The average bleached surface area of corals was 26%. As a consequence of the delayed coral mortality, the average coral cover had declined from 28% to 19%. Most of the recently dead corals were colonized by algae, which increased cover by 15%. The health of surviving coral colonies was threatened by coral disease, with 49% of colonies showing tissue necrosis and 48% of the colony surface area affected.

The fish communities did not appear to be affected: in the 2005 bleaching there was an average of 46 species per 600 m² and fish biomass of 788 kg.ha⁻¹; whereas in 2006 there were 44 species on average and the biomass was 1207 kg.ha⁻¹.

Saint-Barthélemy: Bleaching was recorded first in August 2005 and affected 63% of coral species, 48% of colonies, and an average of 54% of the coral cover. No immediate coral mortality was seen. Coral recruit density was the lowest noted during this season, declining from 50 recruits per 10 m² to 35 recruits per 10 m². Recruitment of juveniles remained low in 2006. Throughout 2006, there was delayed coral mortality and by the end of the year coral communities showed no signs of recovery, with 40% of coral species, 14% of colonies and an average of 20% of the surface of individual colonies still being bleached. By November, the live coral cover had declined by 40%, from 20% before bleaching to 12% afterwards and the dead corals were mainly colonized by algae, with cover increasing by 12%.

The surviving colonies deteriorated significantly throughout 2006; early in the year, tissue necrosis on colonies rose from 18% to 23%, and the colony surface area affected increased from 30% to 48%. The number of infected colonies was still high although many had died from coral disease. By mid-2007, many corals remained pale or partially bleached and had not totally recovered from bleaching, despite normal sea surface temperatures.

The average fish species richness on reefs was 48 species per 600 m² and the fish biomass 751 kg.ha⁻¹ before 2005; and 57 species per 600 m² and a similar fish biomass of 742 kg.ha⁻¹ in 2006

IMPACTS OF HURRICANES IN 2005

The three island groups, Guadeloupe, Martinique, and Saint-Barthélemy and Saint-Martin were not affected by hurricanes in 2005. Previous hurricanes caused some damage: Iris, Luis and Marilyn in 1995; and Lenny in 1999.

SOCIOECONOMIC IMPACTS AND MANAGEMENT RESPONSES

In Guadeloupe, the Grand Cul-de-Sac Marin marine reserve was created in 1987 and an experiment to farm the branching corals *Acropora palmata* and *A. cervicornis* was initiated by the Université des Antilles et de la Guyane in 2005 in the lagoon. The project was achieving encouraging results, until the bleaching event killed all the farmed corals. This indicates that coral farming in an uncontrolled environment may not be a good palliative solution to coral repopulation. The alerts issued about potential bleaching in the MPAs resulted in increased surveillance and monitoring, but there was no other specific management intervention.

CONCLUSIONS - 2005 BLEACHING IN THE FRENCH WEST INDIES.

Coral mortality on the outer reef slopes of the FWI islands ranged between 25% and 52% at different reefs. The variation in mortality was primarily associated with the species composition of the reefs, rather than differing ecological conditions between the reef sites. Coral species showed a large range of bleaching responses to the increased sea temperatures, for example, corals of the families Agaricidae, Favidae and Mussidae were particularly susceptible to bleaching. There was a significant positive correlation between the delayed coral mortality seen and the degree of bleaching in most of the corals. However, some species that bleached rapidly in 2005 recovered well during 2006 e.g. the Poritidae. The hydrocoral, *Millepora squarrosa*, which was common on the reefs previously, appears to have almost disappeared from the FWI and no recruits were seen in 2006 and 2007.

As the three-dimensional structure of the reefs and their capacity to provide shelter for the associated animals have not changed significantly as a result of the bleaching event, the species richness, abundance and community structure of reef fish assemblages have remained similar.

The Netherlands Antilles

INTRODUCTION

There are 2 distinct island groups in the Netherlands Antilles: Bonaire and Curaçao are small oceanic islands 70 km north of Venezuela, with continuous fringing reefs around the islands that are particularly well developed on the leeward sides; and St. Maarten, Saba and St. Eustatius are on the northern arc of the Lesser Antilles and are volcanic with steep cliffs, narrow shelves and limited reef development along the windward coasts. There is limited coastal development on St. Eustatius and Saba, thus anthropogenic effects are minimal. St. Eustatius has true calcareous reefs and also corals growing on the volcanic rocks. The only true reefs on Saba are on the eastern side of the island and most sheer walls are populated by sponges. St. Maarten, which is shared between the Dutch (southern portion) and the French (northern portion), has seen rapid population growth and unmanaged expansion of tourism such that the reefs have been degraded by pollution, deforestation, sedimentation, eutrophication from sewage, recreational boating and anchors, particularly along the south and west coasts. A submerged atoll with actively growing reefs, known as the Saba Bank, is also within Netherlands Antillean waters.

STATUS OF CORAL REEFS PRIOR TO 2005

Bonaire and Curaçao: The greatest diversity of corals are on the leeward (western) side on a 30 m to 150 m wide terrace that slopes gently to about 12 m depth. The prominent corals are *Acropora palmata*, *A. cervicornis* and *Montastraea annularis*, with many large hard coral heads and a variety of gorgonians. After the drop-off at 10–15 m depth, the fore-reef slopes downwards at 30–60 degrees to a sediment bottom between 30 m and 50 m depth. The dominant corals are *M. annularis*, *M. faveolata*, and *Agaricia agaricites*, with *M. cavernosa* and *Stephanocoenia* in deeper waters. On the northern side of Bonaire at Boca Bartol and Playa Benge, the reefs have unusual shallow water spur and groove formations, while the southern facing shore has buttresses that slope steeply down to the sediment platform at 100 m depth. The reefs on Klein Bonaire are varied with some descending steeply close to the shore to a sediment platform at 25–30 m depth. The reefs of Curaçao are similar although there are vertical drop-offs from 6–35 m depth on the eastern side.

The terrace on the eastern side of Bonaire and the north-eastern side of Curaçao extends 100–200 m offshore and to a depth of 12 m, with primarily crustose coralline algae, *Sargassum*, and some gorgonians. The leeward reef slope has less coral cover and abundant brown algae.

On Curaçao, there are about 250 fish species and 55 coral species, with an average of 19 coral species per 200 m² at 6 m depth and 23 species at 12 m. Live coral cover at most sites declined by 10% between 1997 and 2002, with a greater decline at 6 m depth than at 12 m. In 2002, coral cover at 6 m depth on the leeward side of Curaçao was 30–50%, and 30–70% at 12 m. Since 1983, *A. cervicornis* has almost disappeared because of white-band disease, except for a few small stands. *A. palmata* has also declined on both Curaçao and Bonaire. The shallow reefs (0–2 m depth) have completely disappeared since the early 1980s.

There are only 20–30 commercial fishers on Bonaire, but many people fish recreationally. The commercial targets are mostly pelagic species (tuna, dorado, wahoo) caught with hook and line, although trai (throwing nets) and reda (encircling nets) are used to catch bait and big-eye scad respectively. Spear-fishing is illegal, but still occurs, and the use of kanasters (fish traps) is discouraged because of the conflicts they cause with recreational divers. In 2000, reef fish were abundant and diverse and biomass was high. However, in 2002, grouper, conch and lobster were absent from some of Bonaire's reefs and snapper populations were declining. Parrotfish were still abundant because they are considered inedible. Illegal poaching of turtles also occurs, killing as many as 20 turtles per month. Collection for the aquarium trade is banned.

On Curaçao, there are a few hundred artisanal fishers who mostly target pelagic species. Fish traps and gill nets are also used and illegal spear-fishing is still practiced. Fish populations have been severely reduced by heavy fishing pressure; larger fish, particularly groupers and parrotfish, lobsters and conchs are rarely encountered. However, snappers and small parrotfish are still fairly common. Turtles are protected, but are occasionally caught as by-catch.

Saba: There are 35 coral species and some gorgonians, with the dominant corals being *Montastraea anularis*, *M. cavernosa*, and *Diploria strigosa*. Rough seas reduce coral cover in shallow waters (0–7 m) and storms in 1998 and 1999 caused major declines in the abundance of *Acropora palmata*. Coral cover does not exceed 20% because of high sediment loads and frequent benthic algal blooms, and massive corals are often overgrown by bioeroding sponges.

In 1996, there were 28 coral species on the Saba Bank, with 60-90% coral cover. However, AGRRA surveys in December 1999 recorded only 24% coral cover with the highest cover at 21 m depth, and 27.5% dead coral cover. This indicated that disease and bleaching had severely damaged these shallower reefs.

There is limited fishing around Saba and fish populations are considered healthy, but still recovering from historical over-fishing. Grouper and snapper biomass continues to rise after the establishment of the Saba National Marine Park. About 50 fishers (mostly from Saba) fish on the Saba Bank targeting mainly lobsters, red snapper and conch. There was an intensive grouper fishery until populations declined.

St. Eustatius: The offshore reefs begin at 25 m depth with complex spur and groove formations that extend to 60 m. There are steep buttresses on the northern part with 80% coral cover and 35 species. The northern complex has a labyrinth of encrusted ridges, sand channels and huge encrusted rocks, with a fringing reef on the exposed Atlantic side. The leeward side is mostly a sandy plateau with large populations of Queen Conch down to 17 m. Hurricanes Luis and Marilyn (1995) removed large amounts of sediment from the eroding cliffs and severely damaged soft corals and sponges; recovery was rapid.

There are only 15 full- or part-time fishers on St. Eustatius, who use traps to catch fish and lobsters for restaurants. Yellowtail snapper and grouper are highly prized, but locals eat almost any reef fish. Spear-fishing with scuba is illegal, but is still practiced. Many conch were collected until 2001, when regulations were enforced, but some are still taken illegally. Conch populations appear healthy, and turtles are protected, although some poaching of eggs still occurs despite an intensive public awareness campaign.

St. Maarten: Patch reefs with spur and groove structures at 8-18 m depth are concentrated near the east and south-eastern part. In 1999, average hard coral cover was about 30% with bleaching and some diseased corals evident. Hurricane Luis damaged reefs, seagrass beds and beaches, and re-suspended sand smothered *Acropora palmata* stands in shallow water, but these have largely recovered.

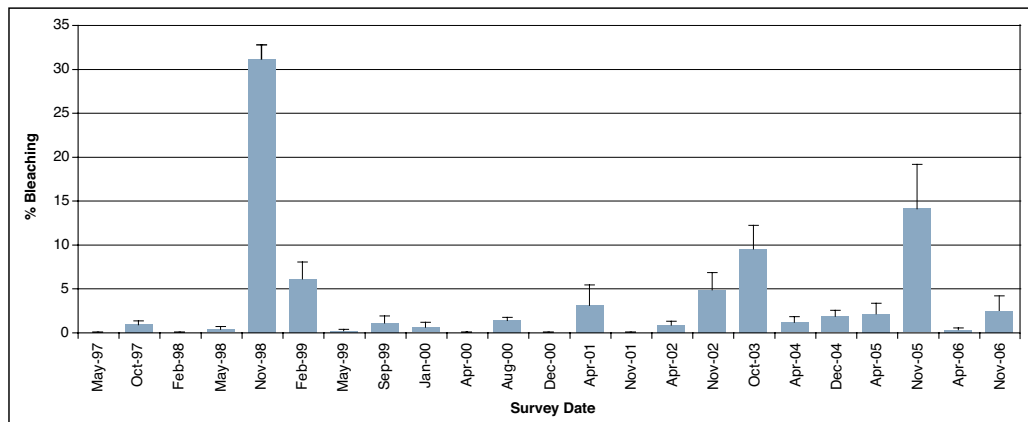
There are about 30 fishers who use fish traps and other artisanal practices. Fish populations are still reasonable, although big groupers are uncommon and conch populations have been depleted.

EFFECTS OF THE 2005 BLEACHING EVENT

Coral bleaching was first noticed in the north on St. Maarten, Saba, and St. Eustatius in late August 2005 and continued until mid-November 2005. Around 80% of coral colonies were bleached on these islands in mid-October. Coral loss on St. Eustatius from June 2005 to June 2006 was 18% at 15 m depth (coral cover dropped from 24% to 6%) and 11% at 25 m (from 26% to 15%). No mortality data are available for St. Maarten and Saba.

Bleaching was less common on Bonaire and Curaçao, with bleaching affecting an average of 14% of coral colonies during November 2005. No mortality was apparent and average coral cover remained at around 40% at 12 m depth and 30% at 6 m, between April 2005 and April 2006.

There was negligible bleaching in 2006 on St. Maarten, Saba, and St. Eustatius and in Bonaire and Curaçao. At Bonaire, 9% of coral colonies were partially bleached in October 2006 (normally the peak bleaching month) and only 2% were completely bleached. Bleaching (pale and fully bleached) affected only 3% of coral colonies on Curaçao, in early November 2006.



Records of the average percentage of hard coral colonies that bleached on Curaçao during the last 10 years show that bleaching was greatest in 1998 and 2005.

IMPACTS OF HURRICANES IN 2005

The northern islands of St. Maarten, St. Eustatius and Saba are regularly hit by hurricanes, whereas Bonaire and Curaçao are south of the path of most Caribbean hurricanes and are only rarely damaged. Thus, the reefs of Bonaire and Curaçao are extremely well developed with very old and large coral heads. The last hurricane damage occurred in 1999 when Hurricane Lenny generated 6 m high waves that struck the lee side of the islands, particularly Bonaire, completely destroying many shallow reef areas to depths of 6 m. In some areas, broken coral heads rolled down the reef slopes causing serious damage at greater depths. In 2004, Hurricane Ivan caused minor damage, but Bonaire and Curaçao were not affected by hurricanes in 2005.

There was no serious hurricane damage during 2005 on St. Maarten, St. Eustatius or Saba, where regular hurricanes have meant that optimum reef development occurs in deeper waters.

SOCIOECONOMIC IMPACTS AND MANAGEMENT RESPONSES

No special management responses resulted from the events of 2005, except that monitoring and surveillance were increased in the MPAs, e.g. in the Bonaire Marine Park, the Curaçao Marine Park, the Saba National Marine Park, and the St. Eustatius Marine Park. In 2006, nature conservation legislation was passed in St. Maarten to provide legal designation of the St. Maarten Marine Park. This will include the levying of a diver fee, and will enable the well-established local NGO (St. Maarten Nature Foundation) to manage the intended marine park. Ten years of funding has already been donated by WWF and other Dutch donors to help management until it becomes financially self sufficient. The NGO employs a park manager and assistant manager to establish moorings, conduct monitoring, and undertake outreach activities.

Barbados

INTRODUCTION

Barbados is the most easterly of the Lesser Antilles island chain. The uplifted fossil coral island is surrounded by a 2-3 km wide shelf that supports a variety of coral reefs. Fringing reefs distinguish the west (leeward) coast and make up 8.4% of the mapped reefs; beyond that there is an almost continuous bank reef parallel to the north, west and south coasts 0.5 to 1.2 km offshore. The crest of this bank reef is 5-35 m deep in the north, west and south and is shallower along the more exposed southeast coast, where it becomes a bank barrier reef. This bank contains 87.1% of the mapped reefs. There are also a few patch reefs at 5-16 m depth between the shore and the bank reef, along the west to southeast coasts.

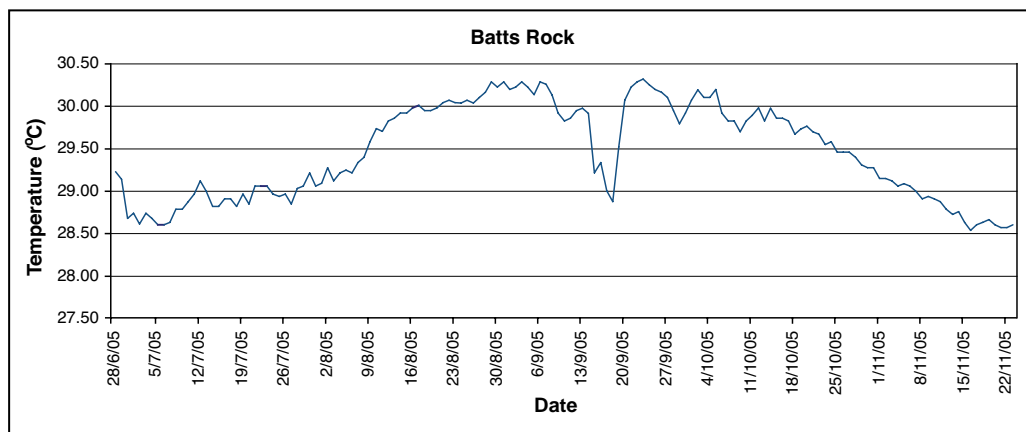
STATUS OF CORAL REEFS PRIOR TO 2005

The inshore fringing reefs have been affected by poor water quality caused by coastal construction, tourism infrastructure and inland agriculture; by storms; and by over-exploitation of fish and corals. Average live coral cover is about 10% in the seaward spur and groove zone (range 1-30%). The offshore bank reefs are relatively undamaged with about 30% coral cover along the crest. These bank reefs are far enough offshore to escape damage from poor water quality, and are also less accessible to fishers. The patch reefs are more variable; they are dominated by hard corals and sponges on the west coast, and soft corals on the more exposed windward coasts, although hard coral cover averages 25%. There have been infrequent bleaching events in south-eastern Caribbean islands; most have occurred within the last decade but were usually of low to moderate intensity.

EFFECTS OF THE 2005 BLEACHING EVENT

NOAA satellite sea surface temperature (SST) data for the eastern Caribbean, including Barbados, showed a coral bleaching 'HotSpot' (SSTs in excess of 1°C above the maximum expected temperatures) that developed to the northeast of Barbados in early June, and strengthened in June-July to cover Barbados and the Lesser Antilles by early August. The HotSpot strengthened during August and September and covered much of the Caribbean Sea by early October. It finally disappeared in late October.

Sea temperatures at 8 m depth on a shallow patch reef confirmed the satellite data, with daily mean temperatures climbing steadily from 28.6°C in late June to more than 30°C in late August and early September. This was 1-2°C above the 'typical' summer maximum. During the second and third weeks of September, strong currents brought cooler water onto the reefs and reduced temperatures by almost 1.5°C, before they returned again to 30°C for the last week of September. Sea temperatures declined to 29.3°C by the end of October and to 28.6°C by the end of November. Benthic temperature loggers at 20 m depth on other sites showed similar temperature patterns to those reported by research divers and dive operators, with widespread warm waters extending to at least 30 m depth.

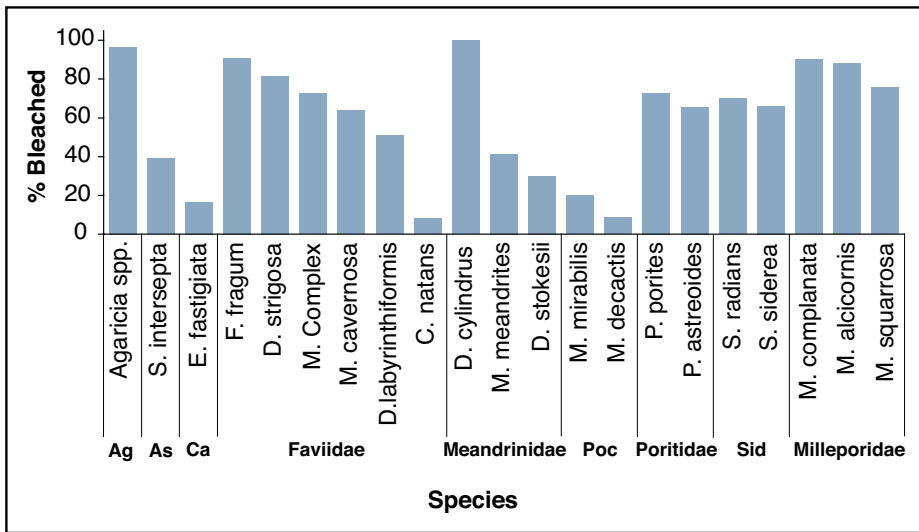


An automatic temperature recorder placed on Batts Rock in 2005 showed that water temperatures rose above the normal bleaching threshold of 29°C in mid-year and continued until late October. Additional temperature recorders paced at North Bellairs, Coconut Court and Atlantis showed that these sites had a similar temperature profile to that of Batts Rock, with a characteristic decline of almost 1.5°C during the second and third weeks of September caused by strong currents that brought cooler water onto the reefs before returning again to 30°C in the last week of September. Such prolonged hot water stress had never been recorded previously in Barbados.

The accumulated heating stress was severe for the eastern Caribbean including Barbados, with Degree Heating Weeks (DHWs) exceeding 5 for much of the summer and reaching a maximum of 13-14 weeks by the end of October and beginning of November 2005.

The first bleached corals were noticed on 24 August at Batts Rock (8 m depth), where several colonies of *Siderastrea siderea* were a pale mauve/blue color. Two days later, similar bleaching of *S. siderea* was seen at 16-20 m depth on the Atlantis bank reef, as well as colonies of *Meandrina meandrites* and the fire corals (*Millepora* spp.). By 3 September, bleaching affected colonies of *Dendrogyra cylindrus* and *Porites astreoides*, and some colonies of *Montastraea annularis*. By mid-September there was widespread bleaching of whole coral colonies in all reef habitats on the west and southwest coasts of Barbados. Dive operators, charter boat captains, fishers and the public reported bleaching. Surveys of 6 reef habitats between mid-September and October 2005 showed severe coral bleaching in all reef habitats, with 59-86% of all hard coral colonies showing some bleaching. Inshore reefs were more severely affected (80.6% of colonies bleached) than offshore reefs (60.5%).

Bleaching also affected 90% of the 29 coral species, with some species being more vulnerable than others. Among the more common species, the most susceptible to bleaching were *D. cylindrus*, *Agaricia* spp., *Favia fragum* and *Millepora complanata*, with 90% or more of colonies affected, whereas fewer than 10% of colonies of *Colpophyllia natans* and *Madracis decactis* bleached. More colonies of *Diploria strigosa* and *P. astreoides* bleached on shallow reefs than on deeper reefs, while the converse was true for *S. siderea*.



The proportion (%) of colonies of the more abundant hard coral species (10 or more colonies observed) that bleached in 2005. Data were collected at 6 reefs around Barbados during Sept/Oct 2005. Abbreviated family names: Ag – Agariciidae, As – Astrocoeniidae, Ca – Caryophylliidae, Poc – Pocilloporidae, Sid – Siderastreidae (Adapted from Oxenford et al. 2007).

This table summarizes the affects of bleaching from late September 2005 to February 2006, at 6 sites around Barbados that have been monitored regularly. Most species and a majority of colonies showed bleaching in shallow and deep water. Live cover estimates are from on-going monitoring at adjacent sites at the time of the survey (adapted from Oxenford et al.

Site, Reef type & Location (depth m)	GPS coordinate	2005				2006		
		Survey date	Coral species bleached of total per 100m ²	Total no. colonies (100m ²)	Mean % colonies bleached (SE)	Survey date	Mean % colonies bleached (SE)	% Live coral cover
Batts Rock, Patch West Coast (8)	N 13°08'08 W 59°38'18	15-Sep	15/20	791	73.8 (6.8)	7-Feb	46.0 (1.7)	29.9
Maycocks, Bank West Coast (22)	N 13°17'32 W 59°39'47	23 Sep	14/16	409	59.1	9-Feb	32.6 (2.7)	37.8
Atlantis, Bank West Coast (16-20)	N 13°07'18 W 59°38'55	30-Sep	15/17	445	63.0 (3.8)	7-Feb	43.7 (6.7)	34
North Bellairs, Fringing West Coast (3-5)	N 13°11'18 W 59°38'31	4-Oct	14/17	1629	82.0 (3.1)	9-Feb	39.7 (8.7)	23.3
Welcome Inn, Bank Southwest Coast (15)	N 13°03'35 W 59°33'25	5-Oct	20/21	621	59.4 (6.9)	6-Feb	43.1 (3.0)	22.9
Coconut Court, Patch Southwest Coast (5-6)	N 13°04'24 W 59°36'11	6-Oct	15/16	713	86.0 (1.3)	6-Feb	19.9 (1.5)	25.8
Overall			26/29	4608	70.6 (4.8)		37.5 (2.5)	28.9

The bleaching event developed rapidly and simultaneously on deep and shallow reefs on both the west and southwest coasts of the island. The first signs of bleaching in the most susceptible species appeared when SSTs rose above 30°C for more than 1 week. As the length of exposure increased, virtually all hard coral species eventually bleached, regardless of whether they were on degraded inshore or healthy offshore reefs. This demonstrated that elevated SSTs can cause coral bleaching on a massive scale and override other stress signals.

The onset of bleaching mortality was rapid in some corals, notably *Millepora* and *Porites porites*, whilst the vast majority remained bleached for many months without significant mortality. In February 2006, there was a mean of 37.5% of colonies still bleached, although mortality was only 3.8%. By June 2006, bleaching persisted in 17.2% of colonies and recent mortality was much higher at 18.7%. Inshore reefs were harder hit, with 20.1% colony mortality, compared with 17.4% mortality for the offshore reefs.

SOCIOECONOMIC IMPACTS AND MANAGEMENT RESPONSES

The events of 2005 are of great concern for tropical islands like Barbados; particularly as the global warming trend is predicted to continue. If SSTs rise by 2-3°C, annual bleaching will probably become common in the Caribbean. Therefore, a well-coordinated, regional monitoring program is required so that more effective management strategies can be implemented at both the regional and local levels.

Coral reefs are recognized as being particularly important to the Barbados economy; thus the Government, through its Coastal Zone Management Unit, has developed a coastal management plan with sections devoted specifically to coral reef protection. This includes a long-term program of monitoring for reefs at 5 yr intervals on 21 west coast, 16 southwest coast fringing and patch reefs and 6 west and southwest coast bank reefs. Previous monitoring indicates that much of the reef deterioration on the west coast was the result of increasing nutrients from the land. In response, the Government constructed the South and West Coast Sewage Treatment Project to reduce pollution. This was part of a coastal zone management plan that outlines permitted coastal development and is enforced through the Coastal Zone Management Act, which protects all corals from physical damage, and the Marine Pollution Control Act, which protects corals from land-based sources of pollution.

The Government has recognized that healthy reefs are more resilient to coral bleaching and other effects of climate change (e.g. potentially greater incidence of coral disease) than degraded reefs. As a result, increasing efforts to reduce anthropogenic stress has become a management priority. Efforts to manage and conserve coral reefs must include all reef types to cover the spectrum of resistance and resilience to bleaching demonstrated by the various coral species in different reef habitats. Small, vulnerable states like Barbados should strive to minimize anthropogenic effects on corals to conserve coral reef resources locally, and put pressure on the international community to reduce global greenhouse gas emissions.

CORAL MORTALITY IN BARBADOS, MARTINIQUE AND THE BRITISH VIRGIN ISLANDS AFTER THE BLEACHING

The eventual fate of stony corals that have bleached is known to be highly variable among sites, and bleaching may persist for many months after seawater temperatures return to 'normal'. The severity of bleaching is likely to be underestimated when surveys are of limited duration and spatial coverage, or focused only on coral color. AGRRA scientists conducted surveys in Barbados, Martinique and the British Virgin Islands using BLAGGRA; a new protocol for rapidly assessing coral condition (available online at www.agrra.org). Prolonged exposure to high sea surface temperatures in 2005 had affected Barbados < Martinique < British Virgin Islands (BVI), and many surviving corals were still partially pale in January 2006; bleaching-related mortality was pronounced in *Agaricia agaricites* (plus *Porites porites* in Barbados and Martinique). In addition, colonies of *Diploria labyrinthiformis* and the *Montastraea annularis* complex were being killed by white plague in the southern BVI. Recent partial-colony mortality estimates of all the ≥ 10 cm corals in belt transects were 5% in Barbados (n = 10 sites), and 11-13% in the southern BVI and Martinique, respectively (n = 7 sites each). Average 'recent loss' of live coral cover in line transects showed similar losses from about 7% in Barbados to about 15% in Martinique and the southern BVI. Despite regaining much of their pigmentation, stony corals continued to die during spring 2006, apparently from the delayed effects of bleaching in Barbados, and, in part, from diseases that were conspicuous for several months in southern Martinique. When most sites were resurveyed in May to early June, recent partial-colony estimates had tripled at repeat sites in Barbados and nearly doubled in Martinique. These dramatic increases are most probably disease-related to the 2005 bleaching 6 months earlier. They demonstrate how essential repeated post-mortem surveys are for at least 6 months after initial bleaching to evaluate the full impact of an event.

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Trinidad and Tobago

INTRODUCTION

The reefs of the island of Tobago are far more extensive than those on the larger island of Trinidad. Tobago's reefs are a mixture of biogenic reefs (built by corals and coralline algae) and geological reefs (base of rock, colonized by hard corals). Most of the reefs are 'shallow' in their structure, ending abruptly in a sand seabed at depths between 15 m and 25 m.

STATUS OF CORAL REEFS PRIOR TO 2005

The most commonly occurring corals are the *Montastraea annularis* complex, which occupied 37% of the substrate, with fire corals (*Millepora* spp.) contributing 12%, and the 'brain' corals, *Colpophyllia natans* and *Diploria strigosa*, contributing 11% and 9% respectively. *Agaricia* spp. and the branching corals (*Porites porites*, *P. furcata* and *P. divaricata*) are far less abundant than on many other Caribbean reefs. This is similar for macro-algae, which covered less than 3% of the substratum, with uncolonized rock accounting for 41%. Coral disease, tissue necrosis or turf-algal/cyanobacterial overgrowth of bleached or unbleached corals has not been recorded during previous surveys, indicating that the reefs were predominantly healthy prior to 2005.

EFFECTS OF THE 2005 BLEACHING EVENT

Following warnings of potential bleaching in 2005, the Buccoo Reef Trust and Coral Cay Conservation assessed 22 discreet reef sites on the Caribbean coast in October/November. Surveys at two deep (~12 m) and two shallow (~7 m) sites showed that coral cover was highly variable around the island. The mean cover was 21.4% (SD ± 12.9%), with the maximum cover recorded being 60% at Pirate's Bay on the north-west coast. Coral cover was greater at deeper sites (~24%) than shallower ones (~19%).

The first bleaching was noticed in *Palythoa* and fire corals (*Millepora*) in September 2005. By October/November, bleaching affected 66% of hard corals (71% on deeper sites and 63% on shallow sites). The extent of bleaching was largely consistent throughout, with most sites showing extensive bleaching (> 85%). However, there was less than 20% bleaching along 9 transects, 5 of which were located near Speyside in the northeast of Tobago. This may indicate either localized tolerance to bleaching or better water quality with either less polluted water or cooler water entering the area.

The incidence of bleaching was highly variable within and between species. *Agaricia agaricites* and *Siderastrea radians* were most affected, with 93% of colonies being bleached. *Madracis mirabilis* and *Acropora palmata* were the least affected species (3% and 0% respectively). The once prominent *A. palmata* is becoming particularly rare throughout the Caribbean, however there was no bleaching seen on the few colonies on or adjacent to the transects. The average incidence of bleaching among species of the *Montastraea annularis* complex was 73%, although there was great variability between these species. For example, at one site at Buccoo Reef, one stand of *M. annularis* exhibited 97% bleaching while bleaching affected only 6% of the surface area of an adjacent stand. This probably demonstrates the presence of bleaching resistant clades (genetic varieties) of the coral and/or the algal symbionts.

By March 2006, only 7% of 180 colonies that had been tagged in November had died. The majority of these corals regained their pigmentation, although partial mortality was evident in 32.5% of the colonies, including some with clear symptoms of coral disease. Mortality was greatest in brain corals (*Colpophyllia natans*, *Diploria strigosa* and *Diploria labyrinthiformis*), with 73% of colonies dying. Most of the reefs had still not recovered from the bleaching event of 2005, with many colonies showing signs of diseases and an apparent rise in colony mortality among the massive corals.

SOCIOECONOMIC IMPACTS AND MANAGEMENT RESPONSES

After the 2005 event, the Buccoo Reef Trust introduced a monitoring program under the regional GEF-IWCAM project and Coral Cay Conservation started coral reef mapping around Tobago. These studies, conducted in partnership with the Tobago House of Assembly, will provide detailed information about the long-term damage to the island's coral reefs from the 2005 bleaching event.

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9. THE EFFECTS OF CORAL BLEACHING IN SOUTHERN TROPICAL AMERICA: BRAZIL, COLOMBIA, AND VENEZUELA

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SUMMARY

- Massive coral bleaching occurred in Southern Tropical America during unusually high sea surface temperatures in 2005. The timing of bleaching varied throughout the region.
- Surveys at 156 sites in Brazil, Colombia and Venezuela show that 2005 was the region's most severe bleaching year, with most bleaching in shallow zones, but the severity varied considerably.
- In Brazil, bleaching started at Itacolomis Reefs in April 2005, after the southern summer.
- In Colombia, reefs at Santa Marta started bleaching 6 months later in October, after the northern summer.
- In Venezuela, the peak bleaching intensity was in November-December 2005, two months later than in the west and north Caribbean. It affected up to 25% of coral colonies but varied greatly among surveyed sites, from 0 to 100%.
- Bleaching was observed in several coral species but only a few, such as *Acropora cervicornis*, *A. palmata*, and *Diploria labyrinthiformis*, suffered mortality.
- Coral reefs less affected by bleaching seem to be related to upwelling zones in the Caribbean.

INTRODUCTION

The Southern Tropical America (STA) Node of the GCRMN includes Costa Rica, Panama, Colombia, Venezuela, and Brazil, with reefs in Pacific, Caribbean and Atlantic waters. The Node is coordinated by the ‘Instituto de Investigaciones Marinas y Costeras’ (INVEMAR) in Colombia, with support from UNEP-CAR/RCU in Jamaica; the Node has been developing coral reef monitoring in this region since 1999.

Most coral reefs in the region have undergone major changes in the last 30 years, particularly during the 1980s, with considerable loss of live coral cover on many reefs and increasing dominance of algae. Nevertheless, high coral cover can still be found on many reefs on both the Caribbean coast (means between 20-40%) and the Pacific coast (means above 40%). Some changes were caused by ‘natural’ agents (ENSO events, bleaching, disease outbreaks, phytoplankton blooms), but others are clearly related directly to human activities (deforestation, increased sedimentation, coastal development, sewage pollution, over-fishing). The 1997-98 El Niño events had little effect on reefs in the region. Monitoring data from the 5 countries indicate that reefs of the STA region did not change significantly between 2000 and 2004. Mass coral bleaching was recorded in the region during 2005 although some reefs were not affected (e.g. Costa Rica). Thus, this report focuses on the effects of coral bleaching events in Brazil, Colombia, and Venezuela.



Map of the Southern Tropical America region.

Brazil

INTRODUCTION

The coral reefs of Brazil have low coral diversity (18 species with 6 endemic) and are discontinuously distributed in 5 major areas along the 2500 km western Atlantic coastline: Touros-Natal has extensive coastal knoll and patch reefs; Pirangi-Maceió has linear coastal reefs and higher species diversity; Todos os Santos Bay-Camamu; Porto Seguro-Cabrália; and the Abrolhos Region to the east and south. The National Marine Park of Abrolhos covers 900 km² and contains the richest coral reefs in Brazil, including the Timbebas Reefs (isolated coastal bank reefs), fringing reefs on offshore volcanic islands of the Abrolhos Archipelago, and the 'chapeirões', which are giant mushroom-shaped coral pinnacles 70 km offshore.

STATUS OF CORAL REEFS PRIOR TO 2005

The first record of coral bleaching was in the Abrolhos area of Eastern Brazil in 1994. In 1998, bleaching was observed in Bahia, north of Salvador City and in the Abrolhos, when sea surface temperatures (SSTs) increased in mid January and peaked between mid March and April, before declining in late May. The SSTs ranged between 29.5°C and 30.5°C; or 1-2°C higher than the long-term average summer maximum of 28.5°C. In 2003, two 'hot spots' occurred in Eastern Brazil (Tinharé and Abrolhos) when SSTs rose in mid February and were 1°C above the long term average in mid March; the hot spots dissipated in late April with up to 20% of coral colonies bleached in Tinharé, and 17% in Abrolhos (SST anomalies are based on 'HotSpot' charts in www.osdpd.noaa.gov/PSB/EPS/SST/climahot.html).

EFFECTS OF THE 2005 BLEACHING EVENT

Two reefs in Southern Bahia, Itacolomis and Abrolhos, were affected by increased SSTs in mid-March 2005 with a maximum rise of 0.75°C above the long-term average. The 'HotSpots' dissipated by the end of April, however, coral bleaching was observed on the Itacolomis Reefs during April, with up to 17% of colonies affected. About 28% of coral colonies were bleached on the Abrolhos reefs in early May. The coincidence of mass coral bleaching events in Eastern Brazil and high SSTs during the last 8 years strongly indicates that these temperature increases are the primary cause of bleaching in the region. Bleaching was mild in Bahia in 2006 with only 6.2±7.1% of colonies bleached on the Abrolhos fringing reefs, compared with 28.3±4.9% in 2005. Live coral cover increased from 11.4 ±5.0% (2005) to 13.5 ±3.5% (2006), with no rise in recent mortality. The amount of dead coral declined from 20.5% (2005) to 17.5% (2006).

Percentage of bleached coral colonies observed on Brazilian reefs in 2005 and 2006 from assessments performed using the AGRRA protocol.

Reefs	Time of observation	Number reef sites	No. colonies observed	Percentage bleached colonies
Itacolomis	April 2005	3	280	4.7 – 17.0
Abrolhos	May 2005	3	399	23.5 – 33.3
Abrolhos	March 2006	6	553	2.0 – 17.0

Colombia

INTRODUCTION

The Caribbean coast of Colombia has reefs on a 40 km wide continental shelf, which are strongly influenced by freshwater and sediment runoff, particularly from the Magdalena River, which is the largest river flowing into the Caribbean. The coral reefs cover more than 2800 km² and are scattered among 26 areas in 3 major groups. The mainland coast has fringing reefs on rocky shores, such as the Santa Marta and Urabá areas. There are many well-developed reefs around offshore islands, including the Islas de San Bernardo and Islas del Rosario, on the continental shelf, and oceanic reef complexes of the San Andrés Archipelago in the Western Caribbean. These are the best developed coral formations, including atolls, banks, barrier reefs, fringing reefs and patch reefs, and comprise more than 75% of Colombia's coral reefs. Pacific reefs are poorly developed, with only Gorgona Island having large coral formations.

STATUS OF CORAL REEFS PRIOR TO 2005

The Caribbean reefs were degraded by pollution, sedimentation, over-fishing, dynamite fishing, and coral mining during the 1980s, with mass mortality of gorgonians, coral bleaching, and declines in sea urchin (*Diadema antillarum*) populations. Bleaching was reported on Colombian Caribbean reefs in 1987, 1990, 1995 and 1998. The 1987 Caribbean-wide event affected the Santa Marta region, Rosario Islands and Bahía Portete (Guajira area), but was poorly documented. During 1990 and 1995, minor bleaching events were observed at Islas del Rosario and Chengue respectively. The 1997-98 El Niño event had little effect on Colombian Caribbean reefs. Coral bleaching affected less than 5% of coral colonies at sites monitored between 1998 and 2001, except in Chengue where it was 10%; but coral mortality was negligible. However, coral communities in Chengue were damaged in late 1999 by Hurricane Lenny, reducing coral cover from 35% to 31%. Colombian Caribbean reefs have changed little since the mid-1990s; coral cover has ranged between 31% and 35% in Chengue Bay, 28% and 32% at Rosario Islands, and 22% and 28% at San Andrés Island. Coral diseases affect less than 5% of coral colonies at all sites, except San Andrés, where 9.1% and 6.3% of colonies were affected in 1999 and 2001 respectively. Dark spot and white plague are the most common coral diseases on Colombia's Caribbean reefs.

IDENTIFICATION OF BLEACHING-SUSCEPTIBLE ZOOXANTHELLAE IN COLOMBIAN CORALS.

Bleached colonies of *Colpophyllia natans*, *Montastraea faveolata*, *M. annularis*, *Agaricia tenuifolia*, and *Porites astreoides* from the coral reefs near Cartagena, Colombia were examined with molecular techniques to identify bleaching resistance or susceptibility in the zooxanthellae; 41.7% of bleached corals contained zooxanthellae clades A, C and D. There were however, many different sub-types of zooxanthellae in clades A and C, with most of these types susceptible to bleaching in 2005. When colonies of *Montastraea faveolata* and *Diploria labyrinthiformis* were re-sampled after the bleaching event, the zooxanthellae were predominantly of thermally tolerant clade D, corresponding with predictions of thermal acclimation (from Maria Clara Hurtado, mar-hurt@uniandes.edu.co and Juan Armando Sánchez, juansanc@uniandes.edu.co)

EFFECTS OF THE 2005 BLEACHING EVENT

Surface waters in Colombia were unusually warm in 2005. The first increases in sea temperature along the Caribbean coast were observed in mid-May and peaked at 1.5-2.5°C higher than the monthly mean in the 3rd and 4th weeks of June. This coincided with the first observations of mass coral bleaching at Islas del Rosario.

The 2005 bleaching event was the most severe for the Colombian Caribbean in the last 25 years. The severity of bleaching varied between the 137 study sites: Rosario and San Bernardo suffered severe bleaching; San Andrés and Providencia were moderately affected; and Santa Marta experienced minimal bleaching. However, corals in the Santa Marta area bleached in October, 4 months after corals on reefs such as Islas del Rosario, which is 200 km to the southwest. This might have been a result of seasonal upwelling peaks that occurred early in the year and in July-August.

There was great variation between sites, with the cover of bleached coral and the proportion of bleached colonies ranging between 0.5-80% and 0.6-100% respectively. However, coral mortality was generally low with less than 5% variation between areas and stations. Most coral species showed some bleaching, especially those in water shallower than 10 m. The greatest bleaching mortality occurred at Islas del Rosario and Islas San Bernardo, mainly among colonies of *Acropora palmata*, *A. cervicornis*, *Diploria labyrinthiformis* and *Millepora alcicornis*. Extensive patches (> 100 m²) of recently dead *A. palmata* and *A. cervicornis* were observed. Subsequent mortality was also observed in tagged colonies that were re-examined two months after the peak of bleaching; some of these colonies were greater than 50 cm in diameter. However, most reefs that suffered bleaching had recovered within 6 months of the onset of the event.

IS COMPETITION FOR SPACE BETWEEN THE ENCRUSTING EXCAVATING SPONGE *CLIONA TENUIS* AND CORALS INFLUENCED BY HIGHER TEMPERATURES?

The rate of lateral overgrowth by excavating sponges was measured to see whether heat stress in corals may make them more susceptible to encroachment. There was no change in rate of lateral spread of the sponge *Cliona tenuis* growing over colonies of the corals *Diploria strigosa* and *Siderastrea siderea* at 5-6 m depths between June 2001 and July 2002, when there was no unusual warming, and in August 2004 and September 2005, which coincided with significant warming. Sponge spreading on *S. siderea* remained constant, but was more variable on *D. strigosa*, irrespective of whether there was partial or total bleaching of the corals. These experiments indicate that there may be differential susceptibility to excessive warming within and between coral species and perhaps between individual sponges (from Juan Carlos Márquez, juancmarquezh@gmail.com; Sven Zea, szea@invemar.org.co; and Mateo López-Victoria, Mateo.Lopez-Victoria@bio.uni-giessen).

Seagrass and mangrove communities monitored at Chengue Bay during 2005 did not show significant changes from the 2005 bleaching event. There was no bleaching in the Colombian Pacific at Malpelo Island in June and Gorgona Island in October.

The impacts of coral bleaching on the reefs of Colombia in 2005 are summarized in this table showing the effect on coral cover and the number of bleached colonies. The effects on the reefs varied considerably within sites with low resultant mortality.

Colombian Caribbean Reefs	Sites Examined	Coral Cover Bleached	Coral Colonies Bleached	Coral Mortality
Islas del Rosario-Cartagena	48	0.5-80%	29-100%	0-2%
Islas San Bernardo	18	0.5-70%	50-100%	0-5%
San Andres	30	1-15%	7-60%	?
Providencia	29	1-10%	0.6-54%	?
Santa Marta-Parque Tayrona	12	1-5%	0-15%	0-1%

IMPACTS OF HURRICANES IN 2005

Hurricane Beta was a moderate category 1 hurricane that passed very close to Providencia and Santa Catalina Islands on 29 October 2005. When 20 sites were examined 15 days later, there was negligible damage to coral reefs, seagrass beds, beaches and mangroves; however, terrestrial vegetation and island infrastructure were severely damaged.

Venezuela

INTRODUCTION

The coast of Venezuela is 2875 km long and with most of this (67%) in the Caribbean where the reefs are found. There are no reefs along the Atlantic coast because of freshwater and sediment runoff, and upwellings. Nearshore coral reefs occur only in Morrocoy National Park and adjacent areas (San Esteban, Turiamo and Ocumare de la Costa), with more than 30 coral species and reef growth to 20 m depth; and Mochima National Park and adjacent reefs (Coche and Cubagua islands), with more than 20 coral species to depths of 14 m. The best developed reefs are around the oceanic islands, especially at Archipelago de Aves, Archipelago Los Roques, La Orchila and La Blanquilla, which have 57 coral species growing to great depths e.g. 57 m.

STATUS OF CORAL REEFS PRIOR TO 2005

The oceanic reefs of Venezuela were once among the few virtually pristine reefs in the Caribbean, but surveys since 2003 showed sites varied between 18% and 51% mean coral cover. The exception was the coastal coral reefs at Parque Nacional Morrocoy (PNM), which were severely degraded in 1996, probably by chemical pollution or a severe phytoplankton bloom, followed by sudden oxygen depletion caused by a climate and oceanic anomaly. Coral cover dropped from 43% to less than 5% at the former CARICOMP reef site of Bajo Caiman. Subsequent CARICOMP surveys at Bajo Cayo Sombrero, one of the few reefs in the park with live corals, indicated that the coral community was in a relatively stable condition, with more than 35%

coral cover. Several coral diseases including yellow band, black band, white diseases, dark spots and ciliate infections had affected the corals.

The table shows the percentage of bleached colonies of zoanthids, octocorals and hard corals in Venezuela, between August 2005 and February 2006. The intensity is recorded as the surface area of the colony affected at oceanic reefs: Isla La Blanquilla (LB) and Parque Nacional Archipiélago Los Roques (Pnalr); and coastal reefs: Parque Nacional Morrocoy (PNM-RFSC) on the western coast and Parque Nacional Mochima (PNM) on the eastern coast that is influenced by upwelling. BCS is the CARICOMP site of Venezuela at PNM-RFSC, which was examined during each sampling period (n = number of colonies surveyed; N = number of sites surveyed at each location).

Surface area of the colony bleached %

Time of observation	Location (N)	Coastal/Oceanic	<10	10-25	25-50	50-75	75-100	Bleached Colonies %	n
Aug-Sep 2005	LB (1)	Oceanic	0.0	1.7	0.4	0.9	0.7	3.7	461
	Pnalr (2)	Oceanic	0.4	0.0	0.0	0.0	0.0	0.4	275
	BCS (1)	Coastal	0.0	0.0	0.0	0.0	0.0	0.0	160
	PNM-RFSC (3)	Coastal	0.0	0.0	0.0	0.0	0.0	0.0	352
Nov-Dec 2005	BCS (2)	Coastal	5.6	4.1	4.6	0.5	11.7	26.5	196
	PNM-RFSC (4)	Coastal	2.2	2.1	1.7	0.8	3.4	10.2	715
Jan-Feb 2006	Pnalr (1)	Oceanic	0.0	0.0	0.0	0.0	0.0	0.0	643
	PNM (1)	Coastal	0.0	0.0	0.0	0.0	0.0	0.0	181
	BCS (1)	Coastal	4.1	2.1	6.7	2.1	2.1	17.1	193

EFFECTS OF THE 2005 BLEACHING EVENT

There was no bleaching among 352 coral colonies at 3 coastal reef sites in August-September. However, there was minor bleaching at 3 oceanic sites, with 1% of 275 colonies affected at Parque Nacional Archipiélago de Los Roques and 4% of 461 colonies at Isla La Blanquilla, but bleaching usually affected less than 10% of the colony surface.

By November-December 2005, up to 25% of 715 coral colonies had bleached at 5 coastal sites in Parque Nacional Morrocoy, with hard corals, soft corals and zoanthids showing bleaching over more than 50% of their surface. Bleaching varied between species: there was 50% bleaching in *Montastraea franksi*; 48% in *M. faveolata*; 14% in *Colpopohyllia natans*; 50% in *Meandrina meandrites*; 16% in *Agaricia agaricites*; 7% in the hydrocoral *Millepora*; 65% in the encrusting octocoral *Erythropodium caribaeorum*; and 85% in the zoanthid *Palythoa mammillosa*.

Bleaching was still evident in January-February 2006 at one coastal reef site in Parque Nacional Morrocoy and 4 oceanic sites at Parque Nacional Archipiélago de Los Roques. Bleaching was not observed at Parque Nacional Archipiélago de Los Roques in the *Acropora palmata* zone (n =

643); however, about 10% of colonies of *Montastraea faveolata* were bleached at other depths. The bleached colonies showed recovery at the coastal site of Cayo Sombrero (BCS), going from 26% bleached (n = 196) in November-December to 17% (n = 193). Severely bleached corals (those with more than 75% of the surface bleached) dropped from 11% in August-September to less than 2% in January-February 2006. There was no bleaching seen at the other 3 coastal reef sites in Parque Nacional Mochima, probably because these sites are in the characteristic upwelling area of the eastern coast.

The 2005 bleaching event also affected other reefs in Venezuela; however, the peak bleaching intensity was 2 months later than other Caribbean sites to the west and north. Bleaching appeared to start on the oceanic reefs, although coastal reefs were eventually more severely affected. The Parque Nacional Mochima was least affected, probably because of the influence of upwelling and lower sea surface temperatures (23°C during surveys) compared with the other reefs (>27°C). Peak bleaching occurred in November-December 2005. There was no increase in the prevalence of coral diseases or loss of coral cover after the 2005 bleaching at any of the 5 monitoring sites.

CONCLUSIONS AND RECOMMENDATIONS

During the Southern and Northern Summers of 2005, the Southern Tropical America region experienced the most severe coral bleaching event for decades. Bleaching was widespread, occurring throughout the region from the oceanic reefs of Colombia in the Southwestern Caribbean to Brazilian reefs in the Western Atlantic. However, the severity of bleaching varied greatly and bleaching mortality was generally low. Nevertheless, extensive areas of *Acropora palmata* and *A. cervicornis* were killed in a few localities, highlighting that these are particularly vulnerable species. Some reefs had minor bleaching (e.g. Santa Marta, Colombia and Parque Nacional Mochima, Venezuela), which could be attributable to the seasonal upwelling in these areas. It is important to understand the differential response to widespread bleaching events so that more resistant coral reefs can be conserved to serve as future sources of larvae for recovery.

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10. MANAGING FOR MASS CORAL BLEACHING: STRATEGIES FOR SUPPORTING SOCIO-ECOLOGICAL RESILIENCE

HEIDI SCHUTTENBERG AND PAUL MARSHALL

INTRODUCTION

This volume documents the severe consequences that climate change is predicted to have for coral reefs worldwide. While there are expected to be many impacts on coral reefs from climate change, the most immediate and dramatic are associated with rising sea temperatures and resultant mass coral bleaching events. These events have already been responsible for long-term damage to more than 16% of the world's reefs and with causing serious, although largely unmeasured, hardship for the people who depend on the reefs. As evidence of these socio-ecological impacts grows, so does attention on the associated management question: ***are there any actions that coral reef managers can implement to help reefs in the face of climate change?***

Traditional management approaches that focus on minimizing or eliminating sources of stress can not address the threat of mass coral bleaching. Coral reef managers are unable to directly mitigate the main cause of mass bleaching; above average water temperatures. This makes mass bleaching a uniquely challenging environmental management problem.

In working with colleagues from around the globe to compile the publication, *A Reef Manager's Guide to Coral Bleaching* (see ref. 5), we determined that there is much that managers can do to help reefs cope with climate change. While reef managers cannot directly limit climate change, there is a rapidly growing body of scientific knowledge that provides the basis for a meaningful response to climate-related threats, such as coral bleaching. Central to this response are strategies for supporting the resilience of coral reef ecosystems and the people that depend on them. This chapter presents the key elements of a resilience-based approach to managing coral reefs in the face of climate change, focusing on:

- Defining socio-ecological resilience;
- Describing the process through which unusually high sea temperatures can lead to loss of the ecological services that reefs provide to people;
- Identifying management opportunities that exist at each stage of this process to minimize negative impacts; and,
- Recommending 5 strategies for supporting socio-ecological resilience to mass coral bleaching.

WHAT DOES IT MEAN TO MANAGE FOR SOCIO-ECOLOGICAL RESILIENCE?

Resilience comes from the Latin, ‘resilere’, which means ‘to spring back’. Managing for socio-ecological resilience recognizes that a process of uncertain change is underway, and it aims to support the ability of the environment and dependent human communities to absorb shocks, regenerate, and reorganize to maintain vital functions and processes. Importantly, socio-ecological resilience explicitly considers that social and ecological systems are intrinsically linked and that the resilience of each component of the system is related to its linkages to other components.

For ecosystems, resilience can be characterized as the capacity to maintain the provision of ecosystem goods and services. For coral reefs, this may mean the capacity of the ecosystem to maintain a dominance of hard corals, adequate structural (habitat) complexity, and positive rates of reef growth. A reef system with low resilience would readily lose coral cover, potentially become dominated by algae, provide reduced habitat, and have a net erosion of reef material. The factors that support coral reef ecosystems’ resilience to mass bleaching events can be broadly grouped into 4 categories: ecosystem condition; biological diversity; connectivity between areas; and local environmental conditions.

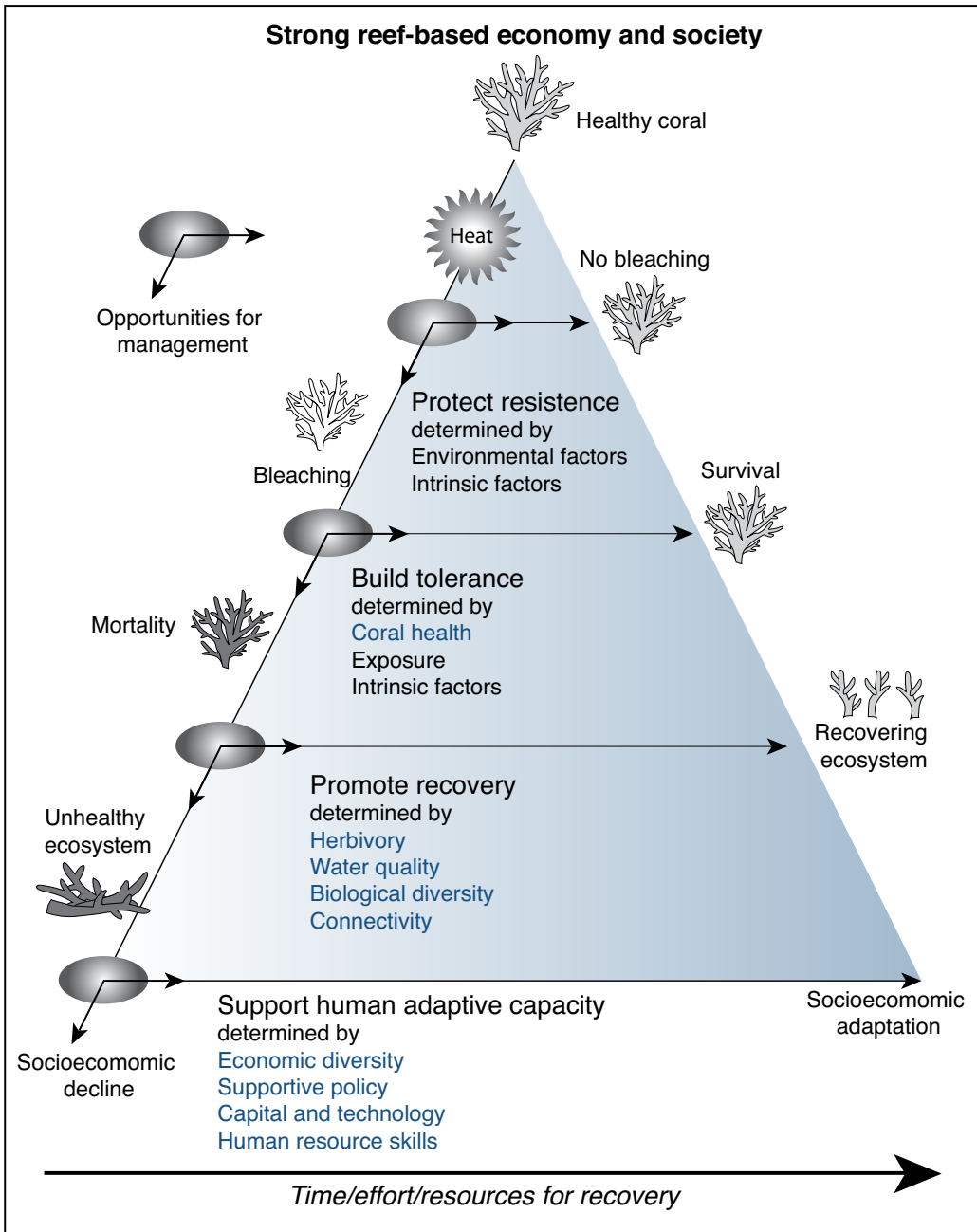
For social systems associated with coral reefs, resilience is determined by the ability to cope with changes in the availability or quality of the goods and services provided by coral reefs. Resilient social systems have the capacity to anticipate, prepare, and adapt to change to minimize the effects on social and economic well-being. The factors that determine the resilience of dependent human communities when coral reefs degrade include people’s skills, resources, attitudes, resource dependency, and attributes of their broader socio-ecological context (4).

Managing for resilience differs from traditional coral reef management in 2 ways. Rather than having a goal to maintain circumstances as they are today, managing for resilience emphasizes protecting the factors that allow the socio-ecological system to respond successfully to disturbance events. Managing for resilience also recognizes that the future may well be determined by unexpected changes, and emphasizes the ability to respond to surprises. We explore how resilience principles can be integrated into coral reef management.

OPPORTUNITIES TO SUPPORT SOCIO-ECOLOGICAL RESILIENCE TO MASS BLEACHING

Four successive conditions determine the ultimate impacts of mass coral bleaching following a regional heat stress event, and each can be a potential focus for management action; as illustrated in the figure below: 1) ‘bleaching resistance’ determines how corals within the area of a regional heat stress event are bleached; 2) if corals do bleach, ‘coral tolerance’ determines how corals either die or regain their zooxanthellae and survive; 3) if there is widespread coral mortality, ‘reef recovery’ determines how the coral reef ecosystem can recover and maintain the characteristics of a coral-dominated ecosystem; and 4) if the coral reef ecosystem remains degraded, ‘human adaptive capacity’ determines how human communities will experience negative socioeconomic consequences.

Each condition is influenced by a suite of factors that combine to determine the resilience or vulnerability of the system. Factors vary in how much they can be changed through management interventions, their relative influence, and the scale (coral colony, ecosystem, or human community) at which they are expressed. The following sections discuss these opportunities for management.



This diagram illustrates the possible opportunities for management intervention in coral reefs that are stressed by a coral bleaching event. Four conditions determine the final outcome: bleaching resistance; coral tolerance; reef recovery; and human adaptive capacity. Each is influenced by factors that can determine the resilience or vulnerability of the system. Factors that can be influenced by local management actions are colored blue. Factors that cannot be influenced are colored black, although these should be considered in the design and placement of management actions to enhance ecosystem resilience (adapted from 6).

Take advantage of resistant coral areas

When regional sea temperatures become unusually high, the effects on coral reefs are variable. Although many corals will bleach, some will not. *What determines the ability of some corals or reef areas to resist bleaching? How can areas that are resistant be used to increase overall resilience of coral reef ecosystems to global climate change?*

A combination of environmental and intrinsic factors determines whether corals eject their zooxanthellae or whether they resist bleaching during a regional heat stress event. Local environmental conditions can support resistance to bleaching by buffering how corals are exposed to unusually high sea temperatures or to sunlight. Three mechanisms can offer protection: shading; cooling; and screening. For example, mountains or cliffs on adjacent land offer shade to some patches of reef, as seen in the high islands of Palau. Some sites may have consistently cooler water as a result of upwelling or proximity to deep water. Sediment and organic matter in turbid waters seems to support coral resistance to bleaching by screening out sunlight; however, unnaturally turbid conditions can also seriously stress corals, thereby undoing any benefits. An additional environmental mechanism providing bleaching resistance is flushing. Strong currents may remove toxins that are the physiological trigger for bleaching, thereby helping corals cope with warmer conditions (7).

Intrinsic factors that influence resistance to bleaching at the colony level include the individual history and genetic composition of the coral and its symbiotic zooxanthellae. This translates to important differences in the bleaching susceptibility of different coral communities. For example, massive, boulder-shaped corals (such as *Porites* and *Favia*) tend to be more resistant to bleaching than branching and plate forming corals (such as *Acropora* and *Pocillopora*). Corals also have some ability to acclimatize to heat and light stress if they are able to survive stressful conditions. Past exposure of coral colonies or communities to stressful conditions can lead to an increased resistance to future bleaching events. The ecological significance of this mechanism is still being examined, because acclimatization of colonies is often short-lived and acclimatization at the community level is often a result of the less resistant corals being lost (3).

Coral reef areas that are naturally resistant to mass bleaching can be incorporated into the design and placement of management initiatives to enhance the overall resilience of the ecosystem. Some consideration has been given to the feasibility of methods for increasing the resistance of other reef areas to bleaching. Such strategies are unlikely to be practicable or cost effective at sufficiently large spatial scales to provide meaningful protection to ecosystems. However, it may be possible to shade, screen, or cool high-value (small) tourism sites to increase their bleaching resistance. These strategies are currently experimental and have the potential for unwanted side effects. They are probably best accomplished through partnerships between industry, scientists, and managers.

Build coral tolerance to mass bleaching

When corals lose their zooxanthellae and bleach, they are not dead. Some bleached corals will survive the heat stress event and regain their zooxanthellae populations; however, corals that bleach but survive the event are in a weakened state. They will probably have lower reproductive capacity, slower growth rates, and greater susceptibility to disease. The ability to survive bleaching events is significant in terms of recovery time. While it may take months or years for

corals to recover from the sub-lethal effects of bleaching, it takes years to decades for reefs to recover after high coral mortality. Therefore, promoting coral survival during bleaching events is a particularly efficient focus for management. ***What allows some corals to be tolerant to mass bleaching? Can management actions be taken to build tolerance and minimize the impacts of mass bleaching events?***

Coral health prior to exposure to heat stress may be the most important factor influencing colony survivorship during bleaching events. Most corals rely heavily on the energy provided by their zooxanthellae, and bleaching effectively robs them of their main energy source. As a result, corals in a bleached state are beginning to starve, and their ability to endure this hardship is likely to be important in determining whether they survive. Like many animals, corals store surplus energy as lipids (fats); corals in good condition have relatively high lipid levels, providing a buffer against periods of low energy supply. For this reason, it is thought that the condition of a coral at the time it bleaches may play a crucial role in determining whether it will survive the period of starvation that follows. Conversely, chronic or acute stresses (such as water pollution or anchor damage) that negatively affect coral condition could increase the risk of corals dying of the additional stress from bleaching (1). Therefore, reducing localized stressors is an important strategy to help corals survive bleaching events.

Some corals, especially species adapted to turbid environments, rely heavily on food particles captured from the water column (heterotrophy) to supplement their energy requirements. These corals may be less dependent on the energy provided by their zooxanthellae and thus less prone to starvation during a bleaching event. A better understanding of coral nutrition could help managers identify tolerant coral communities, allowing them to be incorporated into networks of refugia to enhance overall ecosystem resilience.

Coral health and heterotrophy help increase coral tolerance to bleaching when the heat stress causing a bleaching event is moderate. Heat stress above a critical temperature threshold, however, causes direct physiological damage to corals, exceeding any nutritional factors and leading to death. Both environmental and intrinsic factors are important in determining the extent to which this happens. Thus, local environmental factors have an important influence on the amount of heat stress to which a coral is exposed. Similarly, intrinsic factors, such as genetics, influence the threshold temperature at which a coral dies; some species are able to tolerate higher temperatures than others. These factors contribute to patterns of natural tolerance that can be built into management planning.

Promote coral reef recovery

The rates at which corals can adjust to increases in heat stress are widely considered to be too slow to keep pace with even conservative climate change projections (Chap. 2). As a result, it is unlikely that coral reefs will continue to exist in their current condition. Instead, they will increasingly be in a state of recovery. ***What factors encourage successful ecosystem recovery after mass bleaching events or when other stresses associated with climate change cause high levels of coral mortality? What management actions can be taken to restore or maintain these factors?***

Coral reefs will not necessarily recover to become the same types of reefs they were prior to being severely damaged. The goal in managing for resilience is to have a recovery process

that maintains vital functions and processes, even if the coral reef itself looks quite different from its pre-disturbance state. Ecosystem condition, biological diversity, and connectivity all contribute to ability of the ecosystem to recover to a coral-dominated system, rather than shifting to an algal-dominated state.

Reefs suffering high coral mortality require a long recovery process of recolonisation by coral larvae and asexual reproduction (such as fragmentation) by surviving corals. Successful recruitment depends on many conditions. These include the presence of 'source' reefs to generate new larvae, good water quality that allows spawning and recruitment to succeed, and both strong herbivore (plant/algae eaters) populations and good water quality to ensure there is suitable clear coral rock available for new coral recruits.

High biological diversity supports ecosystem recovery by increasing the chance that vital functions will still be performed despite some degradation of the system. When a diversity of species fulfill a function (for example, branching corals providing habitat for small fish), the loss of a single species will not lead to loss of the function. This 'functional redundancy' is a major quality of resilient systems. A system is less prone to collapse when crucial functions are performed by multiple species that respond differently to stress or disturbance events (called response diversity).

Connectivity plays a central role in determining the capacity of a system to recover or reorganize following a disturbance, by influencing the likelihood that damaged reefs will be replenished from 'seed' reefs or refugia. Much of the connectivity in reef ecosystems depends on intact and healthy non-reef habitats, such as inter-reef hard bottom communities, mangroves, or seagrass beds. These non-reef habitats are particularly important to maintain and regenerate populations, and they will become increasingly critical as reef systems spend more time in recovery mode.

There is ample evidence that coral ecosystems in good condition will recover from coral mortality more successfully than degraded reefs. Healthy reefs are better able to provide the conditions required for the recruitment, survival, and growth of new corals after established corals have been killed by bleaching. Good water quality, an abundant and diverse community of herbivorous fish, and high coral cover are vital aspects of ecosystem quality that facilitate recovery. Therefore, management of local fisheries, water quality, and tourism strongly influence the rate and success of recovery and future coral reef resilience.

Support human adaptive capacity

In addition to supporting ecosystem resilience, actions can be taken to support the human communities that depend on coral reefs, such as fishers and tourism operators. There may be a question as to whether it is appropriate for coral reef or marine protected area (MPA) managers to engage in supporting human adaptive capacity to the affects of climate change. Yet, it is important to recognize that changes in resource condition are likely to result in changes in the patterns of resource use. Engaging with stakeholders during this reorganization will allow managers to build alliances, and gain knowledge and influence to help in effectively adapting management regimes to the new circumstances. As climate change makes life less predictable for resource users and managers, such cooperative, adaptive approaches will be essential to maintain socioeconomic well-being and achieve responsive, effective natural resource planning and management.

People's ability to adapt to degraded coral reefs will depend on their own skills, resources, attitudes, and how their livelihoods are dependent on good coral reef condition, as well as the broader socioeconomic context in which they live. Resource users who have good skills for planning, learning and reorganizing, good financial and social resources, and confidence in their abilities and prospects are likely to be more resilient. Further, meaningful involvement in decision-making on natural resource management can increase user confidence and, concurrently, social resilience to changes in resource access resulting from the impacts of coral bleaching or through changes in management arrangements (4).

Resource dependency and broader socioeconomic issues will also influence how reef users can successfully diversify their activities when coral reefs become degraded. For example, recent studies suggest that dive businesses in population centers are likely to be more capable of responding to changes in reef quality caused by mass bleaching. These operators can shift from a marketing strategy of providing high quality dive sites for experienced divers to a business that provides instruction for new divers or even to boating experiences for non-divers. In comparison, mass bleaching may significantly affect businesses that take divers to remote locations, renowned for exceptional coral reef quality. Tourists may be unwilling to travel so far when high quality reefs are no longer on offer, and businesses in these remote locations may have limited options for business diversification (2).

As coral reef condition degrades, reef users will probably change their resource-use patterns; these changes will have important implications for coastal environmental quality. For example, dive operators may seek ways of establishing artificial reefs. As coral reef fisheries decline, interest and investment in aquaculture may increase. By engaging with stakeholders during this process, coastal managers will have the best chance of developing and implementing strategies that can meet goals for ecological as well as socioeconomic sustainability.

AN AGENDA FOR ACTION

Global climate change and mass coral bleaching are now considered among the greatest threats to the future condition of coral reefs and the services they provide. Although, it may be difficult to see how coral reef managers can respond to such global threats, a closer look at the discussion above reveals that opportunities for management action are present at each stage of the coral bleaching process. The strategies described below suggest ways to take advantage of these opportunities to support the socio-ecological resilience of coral reefs to global climate change. They also illustrate how managers can influence efforts to limit the rate and severity of global climate change. Mitigating climate change will require action by senior decision-makers working in climate change policy forums; however, coral reef managers have an important role to play in informing decision-makers and the general public about the affects of global climate policy on reefs. By taking action on these 5 strategies, coral reef managers will give reefs the best chance of responding to changes in global climate.

Strategy 1. Support efforts to limit sea temperature increases to 2°C and maintain ocean carbonate ion concentrations above 200 $\mu\text{mol kg}^{-1}$.

The rate and extent of warming will determine the window of opportunity for reefs to adjust through acclimatization, adaptation, and other ecological shifts. For example, fewer and less intense sea temperature anomalies will reduce the frequency and severity of bleaching events. Subsequently, this will allow more time for reefs to recover between events that do occur.

These relationships mean that the effectiveness of broader efforts to reduce the rate and extent of global climate change will have significant implications for the effectiveness of local management initiatives. Implementing local management actions, such as those below, will enhance the resilience of coral reefs and ‘buy time’ to implement actions that will reduce the impacts of global climate change. However, if moderate or pessimistic projections for climate change eventuate, the resulting effects on reefs may overwhelm local management efforts aimed at maintaining coral-dominated systems.

The targets for action at a global level were articulated by coral reef managers and scientists at the 3rd International Tropical Marine Environment Management Symposium (ITMEMS) in October 2006. Conference participants adopted the ‘Coral Reefs and Climate Change’ statement, which called on senior decision-makers to “limit climate change to ensure that further increases in sea temperature are limited to 2oC above pre-industrial levels and ocean carbonate ion concentrations do not fall below 200 $\mu\text{mol.kg}^{-1}$ ” (http://www.icriforum.org/secretariat/japangm/docs/Coral_Reefs_Climate_Change_Brief.pdf). These recommendations were based on published projections of the temperatures at which severe bleaching events become an annual phenomenon and reef calcification rates become negative (Chap. 2).

Coral reef managers can provide a powerful impetus for policy responses to climate change by generating their own compelling stories about the plight of reefs under their jurisdiction. Reef managers can document and communicate about the ecological and socioeconomic effects of mass coral bleaching, like those in the Caribbean during 2005. Two publications listed in the references that offer technical guidance on evaluating the impacts of mass bleaching are *A Global Protocol for Assessment and Monitoring of Coral Bleaching* (7) and *A Reef Manager’s Guide to Coral Bleaching* (5). The latter offers suggestions for communicating about mass coral bleaching with key audiences (e.g. decision-makers, stakeholders, colleagues, and the general public) before, during, and after bleaching events.

Strategy 2. Integrate resilience into Marine Protected Area networks.

MPAs are important tools in coral reef management and can help achieve many of the management goals identified above. Traditionally, the principles of MPA selection, design, and management have not specifically addressed the threat of mass bleaching. Integrating the following considerations into existing or developing MPA networks will optimize the role MPAs can play in supporting coral reef ecosystem resilience to mass bleaching:

- *Refugia* - Sites with natural resistance or tolerance to mass coral bleaching should be considered as sites warranting high protection in MPA networks. These ‘lucky’ areas can serve as source reefs that provide new coral larvae to more
- *Representation and replication* – To maximize biological diversity, MPA networks should aim to provide high levels of protection to sufficient areas of all habitat types. Rather than only protecting certain kinds of reefs, networks should aim to include representatives of all reef types and associated habitats at replicate sites. This is a risk-spreading approach that helps to account for the uncertainty associated with global climate change.
- *Connectivity* – Incorporating knowledge about connectivity into the selection and arrangement of sites that will receive higher levels of protection can promote recovery after mass bleaching and other disturbances. Linking highly-protected

areas along prevailing, larvae-carrying currents can replenish downstream reefs, increasing the probability of recovery at multiple coral reef sites. Non-reef areas adjacent to highly-protected reefs may also warrant increased protection because they can become staging areas for coral recruits as they move between reefs.

- Good ecosystem condition – High coral cover, abundant fish populations, and good water quality are all elements of coral reef health that support recovery. Maintaining, enhancing, or restoring these valuable characteristics through management interventions are easier to achieve in some areas than others, because of various attributes of site location and use. In developing MPA networks, it is useful to consider whether additional management protection can be effective in maintaining these resilience-supporting qualities of ecosystem condition.

These principles are already being implemented into MPA networks around the world, including: Palau; the British Virgin Islands; Belize; the Seychelles; Yemen; and the Maldives. The Nature Conservancy's Reef Resilience (R2) Toolkit (8) or website (www.reefresilience.org) has a more detailed discussion of how to identify resilient areas and incorporate these areas into MPA design.

Strategy 3. Reduce local stressors to build coral tolerance to bleaching.

Global climate change will add stress to coral reefs; therefore the removal of local stressors can help corals respond to these new, difficult conditions. Removing chronic local stressors caused by intensive tourism use, water pollution, or over-fishing can increase coral reef health and lipid levels. Corals with higher energy reserves are more likely to survive a bleaching event.

Removal of acute stressors to corals during bleaching events is also likely to increase their ability to survive. Bleached corals are extremely stressed and have a reduced capacity for maintenance of essential functions, such as injury repair, resistance to pathogens, and defence against competitors. A stressed coral is less capable of recovering from physical injuries caused by careless snorkeling, diving, and boat anchoring. Repair of even minor tissue damage may be hindered for a stressed coral, thereby increasing the risk of infection or overgrowth by competing organisms. Acute increases in sediments and pollutants from coastal development or dredging will deliver additional stress to corals that must clear sediment from colony surfaces, wasting precious physiological resources. Bleached corals are also less effective at defending against invasion by microalgae or competing with macroalgae. These coral competitors benefit from increases in nutrients or reductions in the herbivorous fish populations that consume them. Therefore, management can promote coral survival during mass bleaching events by limiting damage from recreation, degraded water quality, and fishing pressures.

Strategy 4. Protect, maintain or enhance the conditions that promote ecosystem recovery.

Coral cover, water quality, and herbivorous fish abundance are critical in determining reef recovery through their influence on processes, including: larval supply; availability of substrate for settlement; coral recruitment rates; and survival of juvenile corals. Traditional management strategies may be based on the assumption that reefs are likely to continue in relatively stable condition. As reefs spend more time in recovery mode, management targets may need to become more conservative to achieve satisfactory water quality, fish abundances, and coral cover. For example, water quality standards and fishery management regimes should

be re-evaluated to determine if they are sufficient to maintain the conditions required for coral recruitment, which is the most vulnerable stage in the coral life cycle. Similarly, reef managers may need to re-direct or limit excessive diving pressure at sites where intense recreational use is reducing coral cover.

Although the natural resilience of reef ecosystems will facilitate recolonisation and subsequent recovery of sites that suffer significant coral mortality, full recovery to pre-disturbance coral cover and diversity can take decades. Recovery can be further delayed, and even inhibited, if the natural resilience of the ecosystem has been reduced by other pressures, such as excess nutrients or sediments, habitat damage, or over-harvesting of crucial functional groups. Therefore, reef managers may wish to consider proposals to assist or accelerate natural recovery processes through active restoration. The diversity and scale of experimental restoration approaches used to date vary widely. They cover habitat modification, coral transplantation, species re-introduction, and enhancement of recruitment. The logistics, costs, and effectiveness of restoration activities, as well as any legal considerations, should be carefully examined before deciding on a course of action.

Strategy 5. Engage stakeholders that rely on coral reefs.

Managers can engage with stakeholders to support their ability to cope with the effects of global climate change by identifying potential socioeconomic and ecological vulnerabilities, communicating about potential impacts, and collaborating on response strategies.

Assessments can be implemented to identify potential impacts and vulnerabilities to the coral reef, the people that depend on the reef, or both. A Reef Manager’s Guide to Coral Bleaching provides further technical guidance on implementing socioeconomic assessments, which can provide information, such as:

- *What are the types of social and economic effects likely to be experienced as a result of global climate change?*
- *Who is likely to be affected?*
- *What opportunities exist to minimize the direct effects of a bleaching event?*
- *How can management responses be designed to minimize the impacts on reef users?*

Managers can also increase socio-ecological resilience by predicting the start and severity of mass bleaching. These predictions not only allow managers to be the source of timely information about bleaching-risk, but also they increase trust and credibility with stakeholders. Social science research has found that resource users are more resilient and better able to cope with changes in resource management when they trust the decision-making process. NOAA’s Coral Reef Watch Program has developed three tools that analyze the likelihood of mass coral bleaching events (<http://coralreefwatch.noaa.gov/>). The book, *A Manager’s Guide...* provides guidance for interpreting the NOAA maps and describes other strategies for predicting mass bleaching.

Effectively communicating with target audiences about the past and future effects of mass bleaching and global climate change will promote awareness among stakeholders and provide information about potential effects to their livelihood. It will also increase support

for management responses. This communication can occur passively, through industry newsletters, web sites, or media articles; or it can occur actively, through engagement in volunteer monitoring programs that provide early warnings about mass bleaching.

At the highest level of engagement, managers and resource users can collaboratively develop a climate change action plan. Such a plan could include strategies for: supporting ecological resilience; diversifying economic activities; enhancing human resource skills; making investments in capital and technology; or reworking related government policies. The Box below draws on recent discussions on the Great Barrier Reef, Australia, and is an example of strategies that could be included in an action plan to help a reef-based tourism industry respond to climate change.

A COLLABORATIVE ACTION STRATEGY TO ADDRESS THE IMPACTS OF CLIMATE CHANGE ON REEF-BASED TOURISM

In November 2005, the Great Barrier Reef Marine Park Authority (GBRMPA) hosted a workshop about climate change for leaders of the Great Barrier Reef (GBR) marine tourism industry. Participants heard presentations from leaders in science, industry, and academia about the potential and expected impacts of climate change on the marine ecosystem, insurance costs, and tourist destination choices. Members of the marine tourism industry then assessed their vulnerability to climate change and devised possible responses and adaptation strategies through participatory breakout groups.

Through workshop discussions, the participants concluded that:

- There is now an overwhelming consensus that climate change is occurring as a result of human activity, and that it is one of the biggest threats to coral reefs worldwide.
- The effects and changes to tourism operations as a result of climate change will be significant and are likely to be directly proportional to overall effects on the Great Barrier Reef.
- There are a number of specific actions that the tourism industry can undertake to help it adapt to climate change.
- The challenges presented will be best addressed by working in partnerships, within the tourism industry, with other industries and with government agencies.
- The key areas where actions can be taken are in marketing and communications; product development and business planning; and environmental and site adaptation.

A review of the actions identified by tourism operators at the forum, suggests six strategies that could be implemented through collaborative industry-government-science partnerships as a way of preparing for the impacts of climate change on reef-based tourism:

1. Better understand climate change implications for reef-based tourism:
 - A. Develop regional predictions of future trends
 - B. Assess business risks
 - C. Evaluate potential business adaptation strategies
 - D. Develop environmental management and engineering strategies
2. Integrate climate change into business planning and operations:
 - A. Implement strategies to maintain industry viability
 - B. Plan for extreme weather events
3. Reduce industry contributions to climate change:
 - A. Reduce greenhouse gas emissions
 - B. Offset air travel emissions
4. Support coral reef resilience to climate change:
 - A. Minimize physical impacts to the reef
 - B. Minimize negative impacts to water quality

CONCLUSIONS

Although coral reef managers cannot directly mitigate climate change, they can take meaningful actions to support the socio-ecological resilience of coral reef ecosystems to climate change. This chapter offers guidance to reef managers on strategies for implementing resilience-based management as a response to coral bleaching and other threats associated with climate change:

- Identify areas that are naturally resistant or tolerant to bleaching and protect them to act as refugia and as seed-banks to replenish more susceptible sites;
- Reduce local stressors to provide bleached reefs with the best chance to survive mass bleaching;
- Protect, maintain, or restore ecosystem condition, biological diversity, and connectivity to promote recovery at sites that experience high mortality;
- Engage with stakeholders about coming changes to build alliances, knowledge, and influence that can help in maintaining socioeconomic well-being and effectively adapt management regimes to the new circumstances; and finally,
- Inform climate change policy decisions by assessing the socioeconomic and ecological impacts of mass coral bleaching and conveying this information to senior decision-makers, colleagues, stakeholders, and the media.

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11. PREDICTIONS FOR THE FUTURE OF THE CARIBBEAN

SIMON DONNER

INTRODUCTION

The 2005 coral bleaching event focused attention on the threat that continued ocean warming poses to Caribbean coral reefs. The most recent assessment by the Intergovernmental Panel on Climate Change (IPCC) concluded that human-induced climate change will cause a 1.8–4.0°C rise in global surface temperature by the end of the 21st century, with slightly less warming over most of the Caribbean. The challenge for climate scientists and coral reef ecologists has been to translate these more coarse projected changes in climate into impacts on coral reefs throughout the diverse Caribbean region. This chapter presents the most recent findings and assesses the overall threat of coral bleaching in the Caribbean over the coming century.

CHALLENGES IN PREDICTING THE FUTURE

Global climate models provide the means to predict how Caribbean coral reefs will respond to future climate change. The models use basic physical and chemical principles to simulate the movement of heat, moisture and energy, through a three-dimensional grid representing the atmosphere, oceans and the land surface in response to natural (solar output, volcanic activity) and human (greenhouse gases, aerosols) heating forces. The simulation of future climates depends in large part on assumptions about demographic, economic and technological change over the 21st century. For example, a 'business-as-usual' emissions scenario envisions a continuation of current activities, like fossil fuel burning and consequent increases in greenhouse gases in the atmosphere, throughout this century.

It is important when examining climate models to understand the difference between greenhouse gas emissions and atmospheric greenhouse gas concentrations. The concentration of greenhouse gases in the atmosphere depends on the rate of emissions and the rate at which the world's ecosystems and the oceans take up or remove greenhouse gases from the atmosphere. Since the rate of carbon dioxide (CO₂) emissions currently exceeds the rate of uptake, stopping the rise in emissions each year is not enough to stop the build-up of atmospheric CO₂. Stabilizing atmospheric CO₂ concentrations and eventually global temperature will require reducing CO₂ emissions well below today's rate.

Scientists use sea surface temperatures (SSTs) from these models to estimate the frequency and severity of coral bleaching events under past, present and future climate scenarios. The NOAA Coral Reef Watch program uses the accumulation of 'Degree Heating Weeks' (equal to one week of temperatures that are 1°C warmer than the maximum monthly temperature the coral reef experiences in the average year) to predict the likelihood of coral bleaching in real-time. Observations indicate coral bleaching begins to occur when the degree heating week or DHW value exceeds 4°C-week and becomes severe when the DHW value exceeds 8°C-week. The preferred method for predicting coral bleaching from the more coarse data provided by global climate models is the accumulation of 'degree heating months'. Similar to a degree heating week, a degree heating month or DHM is equal to one month of temperatures that are 1°C warmer than the maximum monthly temperature (e.g. the average temperature for September in much of the Caribbean). Historical data analysis has shown that DHM values of more than 1°C-month and more than 2°C-month are strong proxies for the lower and upper bleaching thresholds used by the NOAA Coral Reef Watch Program.

The resolution of these climate model forecasts (the size of the grid cells in the computer's picture of the world) is limited by the speed of computers and the complexity of the model. Although the resolution of climate models has improved in recent years, the size of model grid cells is still much larger than features of a coral reef. For example, most of the global climate models used in the most recent IPCC report have a horizontal resolution of only 1 degree of latitude by 1 degree of longitude (~100 km x 100 km). Therefore, the models cannot provide a direct representation of the complex bathymetry and hydrodynamics of many coral reefs.

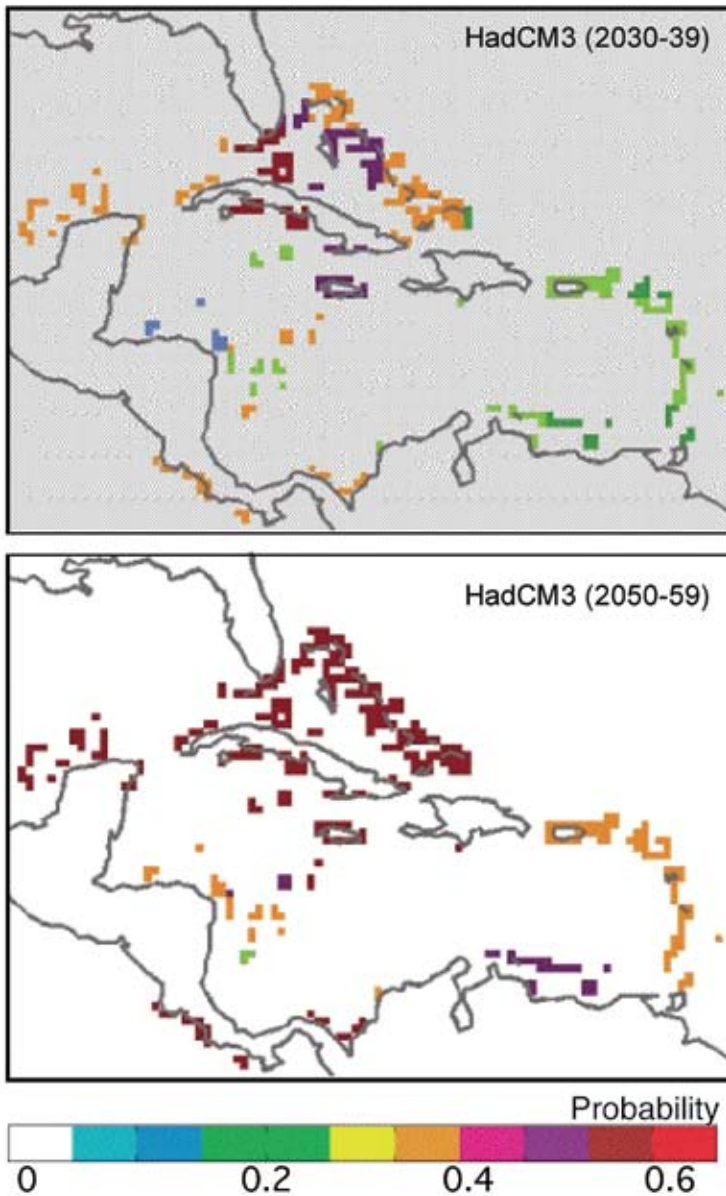
Scientists studying climate change and coral bleaching have resolved the problem either by downscaling (using secondary models or statistical relationships to translate the climate model data to a specific location) or by studying large-scale events, like the 2005 coral bleaching event, that can be described directly by the global climate model itself. This work has provided a general picture of the expected effect of future climate change on the frequency and severity of coral bleaching in the Caribbean.

CORAL BLEACHING IN THE FUTURE

The various studies on climate change and coral bleaching conclude that the majority of the Caribbean is expected to experience conditions that currently lead to coral bleaching (DHM > 1 or 2°C-month) every 2 years, or more, within the next 20 to 50 years.

Whether coral bleaching occurs at these thresholds will depend on the ability of different corals and their symbionts to adapt or acclimate to warmer water temperatures. The warming scenarios indicate that on the majority (>75%) of Caribbean reefs, corals and their symbionts will need to increase their thermal tolerance by 0.2-0.3°C per decade over the next 30-50 years to avoid coral bleaching occurring more than once every 5 years. On about 25% of the reefs, mostly in the north-eastern Caribbean and Lesser Antilles, corals and their symbionts may need to raise their thermal tolerance by twice that amount over the same time-frame.

This forecast for the next 50 years is not very sensitive to the particular future emissions scenario, for two reasons. First, greenhouse gases like CO₂ remain in the atmosphere for decades and even centuries. This causes a lag between the emissions of greenhouse gases and their mean effect on climate. Second, even if the world was determined to dramatically reduce



These two model figures show the estimated frequency of low intensity coral bleaching events across the Caribbean, based on downscaling of results from the Hadley Centre's HadCM3 climate model with more than 90% of Caribbean coral reefs expected to experience DHM > 1°C-month at least every 2 years or more in the 2030s and DHM > 2°C-month at least every 2 years by the 2050s. Greater warming is expected in the north-eastern Caribbean, including parts of Cuba, Florida and the Bahamas. In the most optimistic forecast, based on a climate model less sensitive to greenhouse gas emissions (PCM of the US National Center for Atmospheric Research), low intensity coral bleaching does not become a biannual event on Caribbean reefs until the 2050s.

greenhouse gas emissions, it cannot happen overnight. It will take time, for example, to build a new low-carbon energy generating infrastructure. Therefore, climate models show that the planet is 'committed' to much of the warming predicted in the 'business-as-usual' scenario for the coming decades.

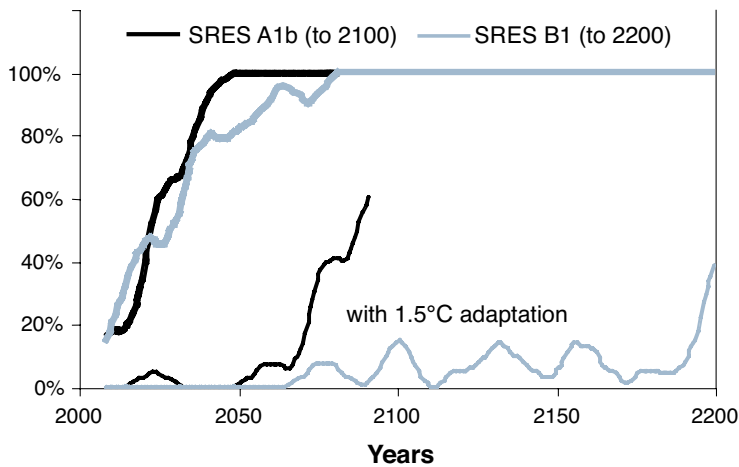
A recent examination of the role of past human activity in the 2005 coral bleaching event helps disentangle the effect of such 'committed' warming, of possible adaptation by corals and of possible efforts to control greenhouse gas emission, on the future of Caribbean coral reefs. By focusing on the average warming over the entire region of the 2005 'HotSpot', it was possible to use climate models to assess the probability of the 2005 bleaching event occurring, with and without the effect of greenhouse gas emissions on the climate.

This analysis shows that the 2005 event would be extremely rare, possibly as low as a 1 in a 1000 year event, without the observed warming since the Industrial Revolution. The build-up of greenhouse gases in the atmosphere has increased the probability of an event like 2005 by at least an order of magnitude, to a less than 1 in a 100 year event. Furthermore, the warming projected to occur over the next 20-30 years should make this once rare occurrence a biannual event. The result is similar in a 'business-as-usual' scenario (SRES A1b) and a lower emissions scenario (SRES B1), in which efforts to reduce emissions cause the concentration of greenhouse gases in the atmosphere to stabilize in the year 2100 at twice the pre-industrial level (about 560 part per million of CO₂ in the atmosphere).

The picture, however, could change with some form of long-term adaptation by most corals and their symbionts. In the 'business-as-usual scenario', if most corals and their symbionts increase their thermal tolerance by 1.5°C, mass coral bleaching will not happen once every 5 years until the latter half of this century. Therefore, if such adaptation is possible, it could postpone the occurrence of frequent damaging bleaching events by 30-50 years or longer. In the lower emissions scenario, mass coral bleaching will not happen more than once every 5 years until the end of the 22nd century if corals are able to adapt by 1.5°C.

Together, these findings indicate that an increase in thermal stress on Caribbean coral reefs in the next 20-30 years is inevitable because of 'committed' warming. However, the findings also show that some temperature adaptation by Caribbean corals and their symbionts could allow time to alter the path of future greenhouse gas emissions and avoid coral bleaching events like 2005 from becoming dangerously common this century.

A small fraction of the warming projected by climate models is actually a result of efforts to decrease another type of atmospheric pollution. The loading of aerosols, from African dust, pollution and volcanic eruptions, can lower Caribbean temperatures by as much as 1-2°C in some years. For example, evidence indicates the eruption of the El Chicon volcano in 1982 (Mexico) and the Mount Pinatubo volcano in 1991 (Philippines), may have protected the Caribbean from high SSTs and extensive coral bleaching. In both cases, the warming in the Caribbean caused by subsequent El Niño events was lower than expected because of high aerosol levels in the atmosphere. Today, the development of cleaner fuel and energy technologies (e.g. low sulphur content) and changes in African land cover in the future is expected to reduce aerosol levels and hence further increase regional temperatures.



This model of the frequency that maximum annual degree heating month (DHM), averaged over the 2005 Caribbean bleaching region, exceeds the upper bleaching threshold of 2°C-month. The results are from the GFDL climate models under a ‘business-as-usual’ scenario (SRES A1b; 2001-2100) and lower emissions scenario (SRES B1; 2001-2200) in which atmospheric CO₂ is stabilized at 560 ppm in the year 2100 scenario. The black line assumes no adaptation by corals and their symbionts; the blue line assumes 1.5°C thermal adaptation.

IMPLICATIONS FOR CORAL REEF HEALTH

“... the Caribbean fits the profile of a vulnerable region: biodiversity is far lower than in the Indo-Pacific; it has been more vulnerable than the Indo-Pacific during past climate fluctuations; it is a relatively enclosed basin with a growing human population in its drainage area and abundant evidence of anthropogenic effects and terrigenous (e.g. runoff-related) influences; there are no other large-scale reef communities in the tropical Atlantic that can serve as refugia or sources of recolonization; and evidence of widely distributed reef stress has already been noted.” (Smith and Buddemeier 1992)

Climate change poses an existential threat to the already heavily disturbed coral reefs of the wider Caribbean. The conditions that currently cause coral bleaching events are expected to occur more frequently (every 2 years) within 20-30 years across much of the Caribbean, especially the northern Caribbean. Thermal adaptation by corals and their symbionts could spare many Caribbean reefs from catastrophic future bleaching events, by allowing time for the world to reduce greenhouse gas emissions and change the long-term climate forecast.

The final effect of the projected increases in the frequency and severity of thermal stress events on individual coral reefs across the Caribbean will depend on the hydrodynamics of the reefs, the health of individual ecosystems, the degree of other direct human pressures, the structure of the coral community, and the adaptability of the individual corals. It will also depend on the response of corals to associated changes in ocean chemistry, hurricane activity and disease transmission.

Caribbean coral reefs subjected to the more frequent bleaching events projected for the future are likely to undergo shifts in community structure. This may already be occurring, with major losses of the *Acropora* coral species since the 1970s. Frequent coral bleaching events, especially when combined with direct human pressures like over-fishing, pollution and sedimentation are expected to keep both coral and fish species richness low and lead to more algal-dominated ecosystems. Aggressive reductions in greenhouse gas emissions and local marine conservation efforts are necessary to avoid the long-term degradation of Caribbean coral reef ecosystems.

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12. SPONSORING ORGANISATIONS, CORAL REEF PROGRAMS AND MONITORING NETWORKS

AFD - AGENCE FRANÇAISE DE DÉVELOPPEMENT

This French government agency contributes to the economic and social development of more than 80 developing countries and the French overseas departments and territories. Total commitments in 2005 were Euro 1601 million. It is both a public establishment and a specialized financial institution, and is responsible for project funding operations as part of France's official development assistance. AFD provides financial assistance for public and private projects in many sectors, including: water resources; finance; urban and rural development; infrastructure, energy and environment; and access to social services (health, education). AFD cooperates with other funding agencies e.g. the World Bank, European Investment Bank, the Asian Development Bank, the European Commission, and administers the French GEF Secretariat (French Global Environment Facility), which integrates environmental considerations within development programs. After the initial focus on renewable resources management (fisheries, forestry, rangelands) and terrestrial environmental programs (protected area management), AFD now includes marine ecosystems in its portfolio and launched the French Coral Reefs Initiative for the South Pacific (CRISP) in 2004. Contact: Dominique Rojat, AFD Paris; rojatl@afd.fr; www.afd.fr.

AGRRA – ATLANTIC AND GULF RAPID REEF ASSESSMENT

International scientists and managers collaborate via AGRRA to determine the regional condition of reefs in the Caribbean and Gulf of Mexico using a rapid assessment protocol. AGRRA has provided baseline data on coral reef health by visual assessments of stony coral cover, mortality and recruitment, macroalgal index, *Diadema* density, abundance and size of key fish families. Consistency among observers is obtained with training workshops. Between 1997 and 2004, AGRRA-sponsored surveys were made at 819 reef sites throughout the Western Atlantic: Bahamas, Belize, Bonaire, Brazil, British Virgin Islands, Curaçao, Cayman Islands, Costa Rica, Cuba, Dominican Republic, Jamaica, Mexico, Panama, Puerto Rico, St. Vincent, Turks and Caicos, US Virgin Islands, US Florida and Flower Garden Banks, Windward Netherlands Antilles, and Venezuela. Survey data (as Access files) and summary products (as Excel and ArcView files) are posted online at www.agrra.org. Special issue #496 of the Atoll Research Bulletin contains the results of the first 20 areas assessed and a synthesis of the early findings. Contact: info@agrra.org.

ARC CENTRE OF EXCELLENCE FOR CORAL REEF STUDIES

The Australian Research Council (ARC) Centre of Excellence for Coral Reef Studies was established in 2005 to build the scientific knowledge that underpins sustainable management of coral reef resources. Headquartered at James Cook University, the ARC Centre of Excellence fosters strong collaborative research links between its partners in 31 countries. A primary goal of the Centre is to develop and undertake reef research programs of international significance that transcend traditional disciplinary, institutional and geographic boundaries. The Centre's researchers undertake fieldwork throughout the Indo-Pacific and Caribbean. The Centre's goal is to build human capacity and expertise internationally. The ARC Centre is the worlds' largest provider of graduate training in coral reef science, with over 100 graduate students from more than 20 countries. Research activities inform reef industries, governments, development agencies, and NGOs worldwide. The Centre's website provides links to over 400 recent publications and a variety of educational material and research services. Contact: Terry Hughes, info@coralcoe.org.au; ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland 4811, Australia. www.coralcoe.org.au

CARICOMP - CARIBBEAN COASTAL MARINE PRODUCTIVITY PROGRAM

This network of Caribbean marine laboratories, parks and reserves has been operating since 1986 with the support of IOC-UNESCO, the MacArthur Foundation, and the U.S. Coral Reef Task Force. CARICOMP monitors long-term variation in ecosystem structure and functioning in coral reefs, seagrasses, and mangroves according to standardised protocols in relatively undisturbed sites. The network also responds to regional events such as coral bleaching events and hurricanes. The Caribbean Coastal Data Centre at the University of the West Indies in Kingston, Jamaica archives the data and makes them available. CARICOMP contributes data to ReefBase and initiated the GCRMN in the Caribbean. In 2000, CARICOMP designed and initiated several sub-regional research projects, including studies of larval linkages and coral diseases, related to long-term management and restoration of Caribbean coastal ecosystems. The CARICOMP program networks institutions in 16 countries: Bahamas, Barbados, Belize, Bermuda, Cayman Islands, Colombia, Costa Rica, Cuba, Dominican Republic, Jamaica, Mexico, Netherlands Antilles, Panama, Puerto Rico, Trinidad and Tobago, and Venezuela. Contacts: John Ogden, jogden@marine.usf.edu; Dale Webber, Centre for Marine Sciences, UWI, Jamaica, dale.webber@uwimona.edu.jm; Marcia Creary, Caribbean Coastal Data Centre, Jamaica, Marcia.Creary@uwimona.edu.jm; www.uwimona.edu.jm/centres/cms/caricomp/.

CBD - CONVENTION ON BIOLOGICAL DIVERSITY

Biological diversity, the variability among living things and the ecosystems that support them, is the foundation upon which human civilizations have been built. Sustaining biodiversity, in the face of considerable threats from human activities, constitutes one of the greatest challenges of the modern era. The Convention on Biological Diversity (CBD), an international legally binding treaty, arose from the Earth Summit in Rio de Janeiro in 1992 and has 190 Parties—virtually universal participation. The objectives of the CBD are: the conservation of biological diversity; the sustainable use of its components; and the fair and equitable sharing of the benefits arising out of the use of genetic resources. The Convention sets out broad commitments by Parties to take action at the national level for the conservation and sustainable use of biological diversity. Since entering into force, the Parties have translated the Convention into programmes of work, including the Jakarta Mandate on marine and coastal biological diversity. The elaborated programme of work on marine and coastal biological diversity addresses coral-reef issues through specific work plans on coral bleaching as well as the physical degradation and destruction of coral reefs, including cold-water corals. Contact: Jihyun Lee, CBD Secretariat, Montreal, Canada, jihyun.lee@cbd.int or www.cbd.int

CI - CONSERVATION INTERNATIONAL

CI is a global, field-based environmental organisation that promotes the protection of biological diversity. Working in more than 30 countries over 4 continents, CI applies innovations in science, economics, policy and community participation to protect the Earth's richest regions of plant and animal diversity. The Marine Rapid Assessment Program (RAP) of the Center for Applied Biodiversity Science at CI organizes scientific expeditions to document marine biodiversity as well as freshwater and terrestrial biodiversity hotspots, and tropical wilderness areas. Their conservation status and diversity are recorded using indicator groups (molluscs, corals and fish), and the results are combined with social, environmental and other ecosystem information to produce recommendations for protective measures to local communities and decision-makers. The main focus of Marine RAP surveys has been the 'coral triangle' in Southeast Asia, which contains the richest coastal and marine biodiversity in the world. Contact: Leah Bunce, Conservation International, 1919 M St. NW, Washington, DC 20036 USA; www.biodiversityscience.org and www.conservation.org, l.bunce@conservation.org

CORAL - THE CORAL REEF ALLIANCE

CORAL is a member-supported, nonprofit organization based in California that is dedicated to protecting the health of coral reefs by integrating ecosystem management, sustainable tourism, and community partnerships. By targeting marine recreation providers, coral park managers, and other community stakeholders, CORAL's programs build cooperative solutions to the challenges facing coral reef destinations around the world. Training, technical assistance, and financial resources provide the basis for building cooperative management strategies, sustainable tourism, and community led conservation projects that improve the health of reefs and the sustainability of reef tourism. In addition, CORAL builds public awareness about coral reefs through various outreach programs, such as the highly acclaimed Dive In To Earth Day. Together, CORAL and its partners are working hard to keep coral reefs alive. Contact: Brian Huse, bhuse@coral.org; www.coral.org

CRTR - CORAL REEF TARGETED RESEARCH & CAPACITY BUILDING FOR MANAGEMENT PROGRAM

This is a leading international coral reef research initiative that provides a coordinated approach to credible, factual and scientifically-proven knowledge to support coral reef management. The CRTR Program is a partnership between the Global Environmental Facility, the World Bank, the University of Queensland (Australia), the United States National Oceanic and Atmospheric Administration (NOAA), and approximately 40 international research institutes and other third parties around the world. The CRTR Program is a proactive research and capacity building partnership that aims to lay the foundation in filling crucial knowledge gaps in the core research areas of coral bleaching, coral reef connectivity, coral diseases, coral restoration and remediation, remote sensing and modelling and decision support. Each of these research areas are facilitated by Working Groups underpinned by the skills of many of the world's leading coral reef researchers. The CRTR also supports four Centres of Excellence in priority regions, serving as important regional centres for building confidence and skills in research, training and capacity building. For contact: The Project Executing Agency, C/- Centre for Marine Studies, The University of Queensland, St Lucia, QLD 4072 Australia, info@gefcoral.org; www.gefcoral.org.

GCRMN - GLOBAL CORAL REEF MONITORING NETWORK

The GCRMN was formed in 1995 as an operational unit of ICRI. The GCRMN is in partnership with ReefBase, Reef Check and NOAA, which constitute the central direction. The GCRMN is sponsored by IOC-UNESCO, UNEP, IUCN, CBD, the World Bank, Reef and Rainforest Research Centre, WorldFish Center and the ICRI Secretariat and central coordination is supported by the US Government and UNEP. IUCN currently Chairs the Management Group of the GCRMN, and the Global Coordinator is hosted at RRRRC and interacts closely with The WorldFish Center. The GCRMN seeks to encourage and coordinate three overlapping levels of monitoring:

- Community - monitoring by communities, fishers, schools, colleges, tourist operators and tourists over broad areas with less detail, to provide information on the reef status and causes of damage using Reef Check methodology and approaches;
- Management - monitoring by predominantly tertiary trained personnel in Government environment or fisheries departments, and universities for moderate coverage of reefs at higher resolution and detail using methods developed in Southeast Asia or comparable methods;
- Research - high resolution monitoring over small scales by scientists and institutes currently monitoring reefs for research.

Equal emphasis is placed on monitoring to gather ecological and socio-economic data, with manuals available for both. A major objective is to produce 2 yearly national, regional and global Status of Coral Reefs Reports, such as those that form the basis for this report. The GCRMN functions as a network of independent Regional Nodes that coordinate training, monitoring and databases within participating countries and institutes in regions based on the UNEP Regional Seas Programme:

- Red Sea and Gulf of Aden - Middle East assisted by the Regional Organisation for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA) Contact: Abdelelah Banajah, Abdelelah.Banajah@persga.org; or Mohammed Kotb mohammed.kotb@persga.org
- The Gulfs – the Persian/Arabian Gulf, Gulf of Oman and the Arabian Sea - assisted by Regional Organisation for the Protection of the Marine Environment (ROPME). Contact: Hassan Mohammadi, ropme@qualitynet.net; or Peyman Eghtesadi, eghtesadi@inco.ac.ir
- Eastern Africa – assisting Kenya, Mozambique, South Africa and Tanzania operating through the CORDIO network in Mombasa. Contact: David Obura in Mombasa, dobura@africaonline.co.ke and Nyawira Muthiga, nmuthiga@wcs.org;
- South Western Indian Ocean Island States - coordinating Comoros, Madagascar, Mauritius, Reunion and Seychelles with assistance from the Global Environment Facility and Indian Ocean Commission. Contact: Jude Bijoux, j.bijoux@scomrt-mpa.sc or Rolph Payet, rolph@seychelles.sc

- South Asia - for India, Maldives and Sri Lanka with support from the CORDIO program of SIDA and IUCN. Contact: the Regional Coordinator in Colombo, Jerker Tamelander, jet@iucnsl.org or Arjan Rajasuriya, Arjan@Nara.Ac.Lk
- South East Asia - for the ASEAN countries with assistance from the ICRAN project and the WorldFish Center, Penang Malaysia. Contact: Karenne Tun, Regional Coordinator, k.tun@cgiar.org or Chou Loke Ming, National University of Singapore, dbsclm@nus.edu.sg
- East and North Asia - Japan is assisting these countries via the Ishigaki International Coral Reef Research and Monitoring Center, and the Nature Conservation Bureau in Japan. Contact: Tadashi Kimura, tkimura@jwrc.or.jp
- Southwest Pacific and Melanesia, for Fiji, Nauru, New Caledonia, Samoa, Solomon Islands, Tuvalu and Vanuatu coordinated through the Institute of Marine Resources, University of the South Pacific and support from Canada. Contacts: Ken MacKay mackay_k@usp.ac.fj or Ed Lovell for Reef Check (lovell@suva.is.com.fj);
- Southeast and Central Pacific, the 'Polynesia Mana Node' for the Cook Islands, French Polynesia, Kiribati, Niue, Tokelau, Tonga and Wallis and Futuna coordinated in French Polynesia from the CRILOBE-EPHE Research Station on Moorea. Contact: Caroline Vieux, carolinev@sprep.org
- Northwest Pacific and Micronesia, the 'MAREPAC Node' for American Samoa, the Marshall Islands, the Federated States of Micronesia (FSM), the Northern Mariana Islands (CNMI), Guam and Palau. Contact: the Palau International Coral Reef Center, Sebastian Marino, smarino@picrc.org;
- Hawaiian Islands – for US islands in the Pacific. Contact: Ruth Kelty, Ruth.Kelty@noaa.gov, or Mark Monaco, mark.monaco@noaa.gov, or Athline Clark, Athline.M.Clark@hawaii.gov
- U.S. Caribbean – for U.S. territories and states of Florida, Flower Garden Banks, Navassa, Puerto Rico, and U.S. Virgin Islands. Contact Mark Monaco, mark.monaco@noaa.gov or www.coralreef.gov; or John.Christensen, John.Christensen@noaa.gov.
- Northern Caribbean and Atlantic region coordinated through the Caribbean Coastal Data Centre, Centre for Marine Sciences, Jamaica for the Greater Antilles to Bermuda. Contact: Loureene Jones, loureene@gmail.com or Marcia Creary Marcia.Creary@uwimona.edu.jm;
- Mesoamerican Barrier Reef System for Mexico, Belize, Guatemala, Honduras. Contact: Noel Jacobs MBRS Project office, Belize, Jacobs_nd@yahoo.com; or Melanie McField WWF Mesoamerican Reef Program, mcfield@bt.net
- Eastern Caribbean, for the Organisation of Eastern Caribbean States (OECS), Trinidad and Tobago, Barbados, and French and Netherlands Caribbean Islands, coordinated by CANARI, with support from UNEP-CAR/RCU from St Lucia. Contact: Claude Bouchon, claude.bouchon@univ-ag.fr; Paul Hoetjes, paul@mina.vomil.an; Angie Brathwaite, abrathwaite@coastal.gov.bb
- Southern Tropical America Node for Costa Rica, Panama, Colombia, Venezuela and Brazil via the 'Instituto de Investigaciones Marinas y Costeras' (INVEMAR) with support from UNEP-CAR/RCU. Contact: Alberto Rodríguez-Ramírez betorod@invemar.org.co.

Central Coordination contact: Clive Wilkinson Global Coordinator clive.wilkinson@rrrc.org.au or David Souter, david.souter@rrrc.org.au at the Reef and Rainforest Research Centre Science, PO Box 772, Townsville, Australia; or Christy Loper, NOAA Silver Springs Maryland USA, Christy.Loper@noaa.gov; Jamie Oliver at WorldFish Center in Penang Malaysia (j.oliver@cgiar.org); or Gregor Hodgson, Reef Check Foundation Los Angeles, gregorh@reefcheck.org.

ICRAN - INTERNATIONAL CORAL REEF ACTION NETWORK

ICRAN was established in 2000 with funding from the United Nations Foundation (UNF). It is a global network of science and conservation organisations working to halt and reverse the decline in health of the world's coral reefs. ICRAN was formed in response to a Call to Action by the ICRI, and supports the implementation,

and regular review of ICRI's Framework for Action. ICRAN has been working at the global, regional and local level in over 30 countries with a range of activities that focus on the prevention and mitigation of coral reef degradation through management, monitoring and public awareness actions. Recognising that reefs and people are inextricably linked, ICRAN works to build resource stewardship within communities by providing opportunities to develop the skills and tools needed to ensure the sustainable use, and the long-term vitality of coral reefs. Actions include alternative livelihoods, training, capacity-building, and the exchange and application of traditional knowledge, and current scientific, economic and social information. E-mail: info@icran.org; www.icran.org

ICRI - INTERNATIONAL CORAL REEF INITIATIVE

The International Coral Reef Initiative (ICRI) is a unique public-private partnership that brings together governments, international organizations, scientific entities, and non-governmental organizations committed to reversing the global degradation of coral reefs and related ecosystems, such as mangrove forests and seagrass meadows, by promoting the conservation and sustainable use of these resources for future generations. Since its establishment in 1995, ICRI has been a driving force behind scientific, governmental and civil society efforts to protect coral reefs and related ecosystems. The ICRI approach is to provide a platform for information sharing, as well as mobilize governments and a wide range of other stakeholders in an effort to improve management practices, increase capacity and political support, and share information on the health of these fragile ecosystems. In particular, ICRI aims to catalyse action that will: improve management practices; increase capacity and political support; and share information on the health of these ecosystems. ICRI has also designated 2008 as the International Year of the Reef (information: www.iyor.org). The ICRI Secretariat is currently hosted by the Governments of Mexico and USA, with an office based at UNEP in the UK; for more information, see www.icriforum.org and to contact the ICRI Secretariat, icri@unep-wcmc.org.

IFRECOR - FRENCH CORAL REEFS INITIATIVE

IFRECOR is the national programme for coral reefs in French tropical overseas territories. IFRECOR, launched in 1999 by the Ministries of Environment and Overseas Territories, developed a National Coral Reef Action Plan to be coordinated by a secretariat in the two Ministries. A national steering committee contains members of parliament, other ministries, social and natural scientists, and NGOs to recommend tasks under the plan. The IFRECOR budget was Euro 2 million over the last 4 years for activities within the 7 French overseas territories with coral reefs. Each territory has a local committee of stakeholders to implement coral reef management. IFRECOR has been successful in raising public awareness of the importance of coral reefs, establishing a French coral reef monitoring network, exchanging coral reef experiences between overseas territories, promoting sustainable uses, involving local communities, and conserving coral reefs. IFRECOR promotes French scientific and technical knowledge at international levels, encourages the participation of French coral reefs specialists in research, assists in developing and managing coral reefs in other countries, and participates in international coral reef monitoring. Since its establishment, IFRECOR, has catalysed an increasing the commitment by government and overseas territories to protect coral reefs and designate MPAs. The next IFRECOR steering committee meeting will be in Guadeloupe, FWI in April 2008. Contact: Bernard Salvat, Ecole Pratique des Hautes Etudes, Université de Perpignan, France, bsalvat@univ-perp.fr

IOC/UNESCO - INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION

The IOC was established under the auspices of UNESCO in 1960 to provide Member States of the United Nations with an essential mechanism for global cooperation in the study of the ocean. For more than 15 years, the IOC has sponsored international research and observation programmes aimed at management of coral reef ecosystems and, more recently, the impacts from climate change and ocean acidification on reef systems. IOC, with UNEP, IUCN and the World Meteorological Organization formed the Global Task Team on Coral Reefs in 1991 to develop global coral reef monitoring, which was the precursor to the GCRMN, with IOC, UNEP, IUCN, World Bank and the CBD now as co-sponsors. The IOC also collaborates with other programmes within UNESCO dealing with coral reefs, including the World Heritage programme, the World Network of Biosphere Reserves, and the Coasts and Small Island Developing States programme. The GCRMN contributes data on coral reef health and resources to the Global Ocean Observing System. Contact: Henrik Enevoldsen, IOC Science and Communication Centre on Harmful Algae, University of Copenhagen, Oster Farimagsgade 2D, 1353 Copenhagen K, Denmark. h.enevoldsen@unesco.org; www.ioc.unesco.org

IUCN- THE WORLD CONSERVATION UNION

Founded in 1948, IUCN brings 1035 States, government agencies and NGOs from 181 countries together in a unique global partnership to influence, encourage and assist societies to conserve the integrity and diversity of nature and to ensure that any use of natural resources is equitable and ecologically sustainable. Its contributions include generating conservation knowledge, setting standards, developing and applying conservation tools, building capacity, and improving policies and global governance. The secretariat is located in Gland, Switzerland, and there are 42 regional and country offices and 10,000 volunteer experts within 6 Commissions, including the World Commission on Protected Areas (WCPA) and the Species Survival Commission (SSC), which focus on particular species, biodiversity conservation and the management of habitats and natural resources. The IUCN Global Marine Program links the members to all IUCN marine activities, including projects and initiatives of the regional offices and Commissions. The program is anchored in IUCN Headquarters, with most of the technical staff in regions with significant marine constituencies and issues. IUCN is a founding member of the GCRMN and the Head of the Marine Programme is the current Chair of the Management Group. Contact: Carl Gustaf Lundin, Global Marine Program IUCN - The World Conservation Union, Rue Mauverney 28, CH-1196 Gland, Switzerland, Marine@iucn.org

ISRS - INTERNATIONAL SOCIETY FOR REEF STUDIES

ISRS, founded in 1980, is the leading organisation for professional scientists, managers, and students of coral reef studies, with a projected membership in 2008 of more than 1000 from 60 countries. The Society promotes the production and dissemination of scientific knowledge and understanding of coral reefs, both living and fossil. It prints and distributes the journal *Coral Reefs* and the newsletter *Reef Encounter*, and offers major research awards and travel support for students. ISRS also assists institutions in developing countries to enhance their library resources. The Society awards the prestigious Darwin Medal for major contributions to coral reef studies, and coordinates and assists host countries with the quadrennial International Coral Reef Symposium, which it co-sponsors. Contact: Richard Aronson, President: raronson@disl.org; www.fit.edu/isrs/

NCAR - NATIONAL CENTER FOR ATMOSPHERIC RESEARCH.

NCAR is a federally funded research and development center sponsored by the National Science Foundation. NCAR scientists collaborate with university colleagues to study climate, air chemistry, storms and basic weather processes, the Sun and its effects on the Earth, and how human activities affect and are affected by the atmospheric environment. NCAR also provides computing and observing services to researchers working in areas related to the atmosphere. The NCAR Institute for the Study of Society and Environment conducts research on the ecological and societal impacts of climate and weather, including studies of coral reef ecosystem vulnerability to global warming, ocean acidification, and other aspects of climate change. Scientists study these interactions to improve projections of the impacts of climate on ecosystems and natural resources, and to assist in forward-looking management strategies. NCAR is managed by the University Corporation for Atmospheric Research, a not-for-profit consortium of universities. Contact: Lucy Warner, UCAR Communications, 3300 Mitchell Lane, Boulder, CO 80301 USA, lwarner@ucar.edu; www.ncar.edu.

NOAA - NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION USA

NOAA is an agency of the Department of Commerce dedicated to enhancing public health and safety and promoting sound economic interests by researching and predicting weather and climate-related events and protecting the coastal and marine resources of the USA. NOAA is a steward of U.S. marine resources and co-chairs the U.S. Coral Reef Task Force, which is responsible for coordinating U.S. government efforts to conserve coral reefs. The NOAA Coral Reef Conservation Program (CRCP) addresses priorities in the National Action Plan to Conserve Coral Reefs and the National Coral Reef Action Strategy such as mapping, monitoring, research, education and managing reef resources. The CRCP facilitates and supports partnerships with scientific, private, government and NGO groups at local, state, federal and international levels. The goal is to support effective management and sound science to preserve, sustain and restore valuable coral reef ecosystems. Contact: NOAA Coral Reef Conservation Program, 1305 East-West Highway, N/OCRM, Silver Spring, MD, 20910 USA; coralreef@noaa.gov; www.coralreef.noaa.gov.

RAMSAR - CONVENTION ON WETLANDS

The Ramsar Convention on Wetlands, was signed in Ramsar, Iran in 1971 and broadly defines 'wetlands' to include all 'areas of marine water the depth of which at low tide does not exceed six metres' (Article 1.1). In the designation of Wetlands of International Importance (Ramsar sites) it also explicitly allows the inclusion of 'coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six metres at low tide lying within the wetlands' (Article 2.1). Coral reefs are recognised as a category of marine and coastal wetlands in the Ramsar Wetlands classification. Specific guidance on the identification and designation of coral reefs is provided in Ramsar Wise Use Handbook 14, 3rd edition 2007 (available on: www.ramsar.org/lib/lib_handbooks2006_e.htm). There are 63 designated Ramsar sites that include coral reefs, including important sites in Australia, Brazil, Costa Rica, Cuba, Djibouti, Ecuador, France (overseas territories), Guinea, Honduras, Islamic Republic of Iran, Mexico, Nicaragua, Philippines, South Africa, Thailand, The Netherlands (overseas territories), United Kingdom (overseas territories) and Venezuela, but many important coral reefs have yet to be designated as Ramsar sites, and a priority for further designation of coral reef Ramsar sites has been recognised by the Convention's Contracting Parties. Contact: Nick Davidson, Deputy Secretary General, Ramsar Secretariat, Rue Mauverney 28, CH-1196 Gland, Switzerland; davidson@ramsar.org; www.ramsar.org/types_coral.htm; information on coral reef Ramsar sites at Ramsar Sites Information Service; www.wetlands.org/rsis/.

REEF CHECK FOUNDATION

The Reef Check Foundation is dedicated to research, education and conservation with respect to two ecosystems: tropical coral reefs; and California rocky reefs. With headquarters in Los Angeles and volunteer teams in more than 90 countries and territories, Reef Check works to create partnerships among community volunteers, government agencies, businesses, universities and other non-profits. Reef Check maintains 4 major initiatives: to educate the public about the value of reef ecosystems and the current crisis affecting marine life; to create a global network of volunteer teams trained in Reef Check's scientific methods who regularly monitor and report on reef health; to facilitate collaborations that produce ecologically sound and economically sustainable solutions; and to stimulate local community action to protect remaining pristine reefs and rehabilitate damaged reefs worldwide. Contact: Gregor Hodgson or Cori Kane, PO Box 8533, Calabasas, CA 91372; rcinfo@reefcheck.org; www.ReefCheck.org

RRRC - REEF AND RAINFOREST RESEARCH CENTRE.

The Reef and Rainforest Research Centre Limited (RRRC) was established in 2006 to implement the Australian Government's Marine and Tropical Sciences Research Facility (MTSRF) in North Queensland. As the successor entity to the CRC Reef (Cooperative Research Centre) and the CRC Rainforest, the RRRC builds upon the knowledge base developed through the CRC to ensure that targeted, focused research is delivered to appropriate end-users and management agencies. The RRRC manages scientific projects that comprehensively address issues of concern for the sustainable use, management and protection of the Great Barrier Reef (GBR) and its catchments as well as the issues for the rainforests of the Wet Tropics, through the generation and transfer of world-class research and the sharing of knowledge. Great Barrier Reef research conducted through the RRRC includes studies into the impacts of climate change and destructive pest outbreaks on the coral reef systems, the ecological and socio-economic effects of the marine protected areas in the GBR, coastal zone risk and threats and advances in sustainable use of the GBR. Contact: Sheriden Morris, Sheriden.morris@rrrc.org.au; www.rrrc.org.au

UNEP - UNITED NATIONS ENVIRONMENT PROGRAMME

The mission of UNEP is to provide leadership and encourage partnerships in caring for the environment by inspiring, informing, and enabling nations and peoples to improve their quality of life without compromising that of future generations. UNEP makes a particular effort to nurture frameworks and initiatives at the local, national, regional and global level which enhance the participation of governments and civil society - the private sector, scientific community, NGOs and youth - in working together towards sustainable utilisation of natural resources. The challenge before UNEP is to implement an environmental agenda that is integrated strategically with the goals of economic development and social well-being; an agenda for sustainable development. Contact: UNEP, PO Box 30552, Nairobi, Kenya; info@unep.org; www.unep.org

UNEP - CORAL REEF UNIT (CRU)

The CRU is the focal point within UNEP and the UN system to guide and mobilize policies and actions to support the conservation and sustainable use of coral reefs to safeguard their biological and biodiversity functions, which provide goods and services for the benefit of people and the sustainable development of dependant communities. Co-located with other coral reef resources at UNEP-WCMC, the CRU works closely with UNEP divisions/programs and international partners such as the International Coral Reef Initiative (ICRI) and Operational Networks. CRU activities include: supporting international collaboration to reverse coral reef degradation; cooperating to promote the political understanding of the importance of coral reefs; reviewing and integrating information on international policies related to coral reefs; and promoting innovative partnerships to address new and emerging coral reef issues, such as cold-water coral reefs. Contact: Stefan Hain, UNEP Coral Reef Unit, 219 Huntingdon Road, Cambridge, CB3 0DL, UK; stefan.hain@unep-wcmc.org.

UNEP – REGIONAL COORDINATING UNIT FOR THE CARIBBEAN ENVIRONMENT PROGRAMME (UNEP-CEP)

The Caribbean Environment Programme (CEP) of UNEP helps nations protect the marine environment and promotes sustainable development in the Wider Caribbean Region (WCR). CEP is managed by and for the countries of the region under a legal framework they created in 1983, known as the Convention for the Protection and Development of the Marine Environment of the Wider Caribbean Region (Cartagena Convention) which is supported by three Protocols, on: biodiversity (SPAW); land-based sources of pollution (LBS); and oil spills response. The CEP works as a facilitator, educator, and catalyst to co-ordinate activities and build the capacity of all member governments to manage their coastal environments and build sustainable and coastal economies. The 28 member States and 8 Territories that created the CEP, encircle the Caribbean Sea and Gulf of Mexico. Contact: Nelson Andrade Colmenares, Coordinator, 14 – 20 Port Royal Street, Kingston, Jamaica, West Indies; rcu@cep.unep.org; www.cep.unep.org.

UNEP - WORLD CONSERVATION MONITORING CENTRE

UNEP-WCMC is the biodiversity assessment centre of UNEP with a major coral reef focus. This includes critical marine and coastal ecosystem mapping, a global database on marine protected areas, and the global distribution of threats, including coral disease. Reef associated ecosystems have been a major focus since the first Status of Coral Reefs of the World: 1998 report. UNEP-WCMC has published the World Atlases of Coral Reefs and Seagrasses, and work is underway to revise mangrove data into a new global atlas for publication in 2008. Future work at UNEP-WCMC will focus on a better understanding the value of ecosystem good and services, especially coral reefs and associated ecosystems, in marine protected areas; and the importance of ecosystem biodiversity to people. Contact: Kristian Teleki, One Ocean Programme, UNEP-World Conservation Monitoring Centre, 219 Huntingdon Road, Cambridge, CB3 0DL, UK; oneocean@unep-wcmc.org or www.unep-wcmc.org.

UNESCO WORLD HERITAGE CENTRE

The UNESCO World Heritage Centre (WHC), based in Paris, was established to assure the Secretariat of the 1972 Convention concerning the protection of the World Cultural and Natural Heritage (World Heritage Convention). The activities include assisting member states prepare World Heritage nominations, following the state of conservation of inscribed properties as well as providing financial or technical support from the World Heritage Fund or from extra-budgetary sources for the conservation of the sites. The WHC is working towards a more integrated approach towards marine World Heritage sites, and the recently established Marine Programme aims: to increase awareness of the Convention as a legal tool for achieving conservation of marine and coastal ecosystems; to contribute to improving the state of conservation of existing marine World Heritage sites; to promote nominations of marine properties including serial and transboundary sites; and to establish partnerships to build a network of support for marine World Heritage. Contact: Marc Patry, UNESCO World Heritage Centre, 7 place de Fontenoy, 75352 Paris 07 Sp, France; m. patry@unesco.org

USCRTF - UNITED STATES CORAL REEF TASK FORCE

The USCRTF was established by Presidential Executive Order in 1998 to lead U.S. efforts to preserve and protect coral reef ecosystems. The USCRTF, co-chaired by the Departments of Commerce and the Interior,

includes 12 federal agencies responsible for coral reef conservation, 7 state and territory partners, and 3 freely associated states. The USCRTF adopted the U.S. National Action Plan to Conserve Coral Reefs in 2000, the first U.S. plan to comprehensively address the most pressing threats to coral reefs. The Action Plan identifies two fundamental themes for immediate and sustained action: understand coral reef ecosystems and the natural and anthropogenic processes that determine their health and viability; and reduce the adverse impacts of human activities on coral reefs and associated ecosystems. The USCRTF launched initiatives to help implement the Action Plan, including developing 3-year Local Action Strategies in each jurisdiction to address key threats to reefs. Contact: U.S. Coral Reef Task Force Secretariat, National Oceanic and Atmospheric Administration, Office of Response and Restoration, 1305 East-West Highway, N/ORR, Silver Spring, MD, 20910; www.coralreef.gov.

U.S. DEPARTMENT OF STATE

The State Department leads the United States in its relationships with foreign governments, international organizations, and the people of other countries. Through its diplomatic efforts, the Department is dedicated to creating a more secure, democratic and prosperous world for the benefit of the American people and the international community. Within the Department, the Bureau of Oceans and International Environmental and Scientific Affairs is responsible for advancing sustainable development and natural resource conservation, including actions related to coral reefs and coral reef ecosystems, through a wide variety of international treaties, organizations, initiatives and public-private partnerships. Contact: The U.S. Department of State, Bureau of Oceans and International Environmental and Scientific Affairs, Office of Ecology and Natural Resource Conservation, Room 4333, 2201 C Street N.W., Washington D.C., 20520; www.sdp.gov/sdp/initiative/icri.

WORLD BANK – ENVIRONMENT DEPARTMENT

The World Bank is an international financial institution dedicated to the alleviation of poverty. The Environment plays a crucial role in determining the physical and social well being of people. While poverty is exacerbated by deteriorating conditions in land, water and air quality, economic growth and the well being of communities in much of the developing world, continues to depend on natural wealth and the production of environmental goods and services. As a result, the Bank is committed to integrating environmental sustainability into its programs, across sectors and regions and through its various financial instruments. Reducing vulnerability to climate change, improving people's health, and enhancing livelihoods through protecting ecosystem services and the environment are the hallmarks of the Bank's Environment Strategy. Support for coral reef conservation and sustainable use is consistent with this theme, as it potentially affects hundreds of millions of people around the world. The challenge for the Bank and its many partners in coral reef conservation, such as ICRI and GCRMN, will be to help communities capture the benefits from the sound management of coral reefs to meet immediate needs, while at the same time ensuring the sustainability of these vital systems for generations to come. For information on the Environment Department, contact: Marea Hatzios, Environment Department, The World Bank, 1818 H St. NW, Washington, DC 20433 USA, Mhatzios@worldbank.org; www.worldbank.org/icm; www.gefcoral.org

WORLD FISH CENTER

Formerly known as ICLARM, it is committed to contributing to food security and poverty eradication in developing countries. The efforts focus on benefiting poor people, and conserving aquatic resources and the environment. The organisation aims for poverty eradication; a healthier, better nourished human family; reduced pressure on fragile natural resources; and people-centered policies for sustainable development. WorldFish Center is an autonomous, non-governmental, non-profit organisation, established as an international center in 1977, with new headquarters in Penang, Malaysia and the focus for international efforts to tackle the major aquatic challenges affecting the developing world and to demonstrate solutions to resources managers worldwide. Contact: PO Box 500 GPO, 10670 Penang, Malaysia. Jamie Oliver, l.oliver@cgiar.org; www.cgiar.org/iclarm/

WRI - WORLD RESOURCES INSTITUTE

WRI is assisting coastal resource management and coral reef protection by providing comprehensive information on threats to coral reefs, economic value of the goods and services and losses that will result from reef degradation. The regional projects are implemented in close collaboration with partners, following the more-detailed global Reefs at Risk analysis from 1998. Reefs at Risk in Southeast Asia was released in 2002 and

Reefs at Risk in the Caribbean in 2004, with the specific goals to: 1. improve the information base on threats to, status of, and protection of coral reefs in a region, by collecting, improving, and integrating information; 2. model threats to coral reefs based on population and development patterns, land use change, and the location and intensity of specific activities that degrade coral reefs; 3. develop a geographic information system (GIS)-based tool for local-level evaluation of development scenarios and related implications for coral reef health and economic value; 4. evaluate economic losses likely to result from coral reef degradation; and 5. raise awareness of human threats to coral reefs through wide dissemination of project results. All data (including GIS data sets) are on www.reefsatrisk.wri.org. WRI is currently working on economic valuation of coral reefs in the Eastern Caribbean and Belize. Contact: Laretta Burke, World Resources Institute, Washington, DC 20002, USA: lauretta@wri.org or Emily Cooper, ecooper@wri.org.

WWF – ‘THE GLOBAL CONSERVATION ORGANIZATION’

WWF is one of the world’s largest and most experienced independent conservation organizations, with almost 5 million supporters and a global network active in more than 100 countries. WWF’s mission is to stop the degradation of the planet’s natural environment and build a future in which humans live in harmony with nature, by: conserving the world’s biological diversity; ensuring that the use of renewable natural resources is sustainable and promoting the reduction of pollution and wasteful consumption. Using our global scope, credibility, and expertise, WWF’s Global Marine Programme develops and advocates solutions for sustainable fishing and the creation and management of Marine Protected Areas (MPAs). As part of our efforts to support well-managed fisheries and stop destructive fishing practices, WWF promotes economic incentives, consumer initiatives, and trade management measures that encourage sustainable fisheries. WWF has also been active in coral reef conservation since the early 1970s, carrying out over 100 related projects in more than 30 countries. Our work to redress the inadequate protection of our oceans, reefs and coasts involves; establishing and implementing a network of ecologically representative, well-managed MPAs; improving the management and reducing external threats, such as climate change, to MPAs. Contact: Helen Fox, helen.fox@wwfus.org or Lara Hansen, lara.hansen@wwfus.org, WWF, 1250 Twenty-Fourth Street, NW, Washington, DC 20037; www.panda.org

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14. LIST OF ACRONYMS

AGRRA	Atlantic and Gulf Rapid Reef Assessment
AIMS	Australian Institute of Marine Science
CARICOMP	Caribbean Coastal Marine Productivity Program
CATIE	Centro Agronomico Tropical de Investigacion y Ensenanza
CBD	Convention on Biological Diversity
CI	Conservation International
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CORAL	The Coral Reef Alliance
CSD	Convention for Sustainable Development
EIA	Environmental Impact Assessment
ENSO	El Niño Southern Oscillation
GBR	Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
GCRMN	Global Coral Reef Monitoring Network
GEF	Global Environment Facility
GIS	Global Information System
ICAM	Integrated Coastal Area Management
ICM	Integrated Coastal Management
ICZM	Integrated Coastal Zone Management
ICRAN	International Coral Reef Action Network
ICRI	International Coral Reef Initiative
IFRECOR	'French Coral Reef Initiative'
IOC	Intergovernmental Oceanographic Commission of UNESCO
ISRS	International Society for Reef Studies
IPCC	Intergovernmental Panel on Climate Change
IUCN	The World Conservation Union
MAB	Man and the Biosphere site of UNESCO
MARPOL	International Convention of the Prevention of Pollution from Ships
MPA	Marine Protected Area
NCAR	National Center for Atmospheric Research
NGO	Non-Governmental Organisation
NOAA	National Oceanic and Atmospheric Administration (of USA)
Ramsar	International Convention on Wetlands
RRRC	Reef and Rainforest Research Centre.
SCUBA	Self-contained underwater breathing apparatus
UNEP	United Nations Environment Programme
UNEP-CEP	Regional Coordinating Unit for the Caribbean Environment Programme
UNESCO	United Nations Educational Scientific and Cultural Organisation
UNF	United Nations Foundation
USAID	US Agency for International Development
USCRTF	United States Coral Reef Task Force
UV	Ultraviolet radiation
WCMC	World Conservation Monitoring Centre
WHS	World Heritage Site
WRI	World Resources Institute
WWF	the global conservation organization

