Executive Summary

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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

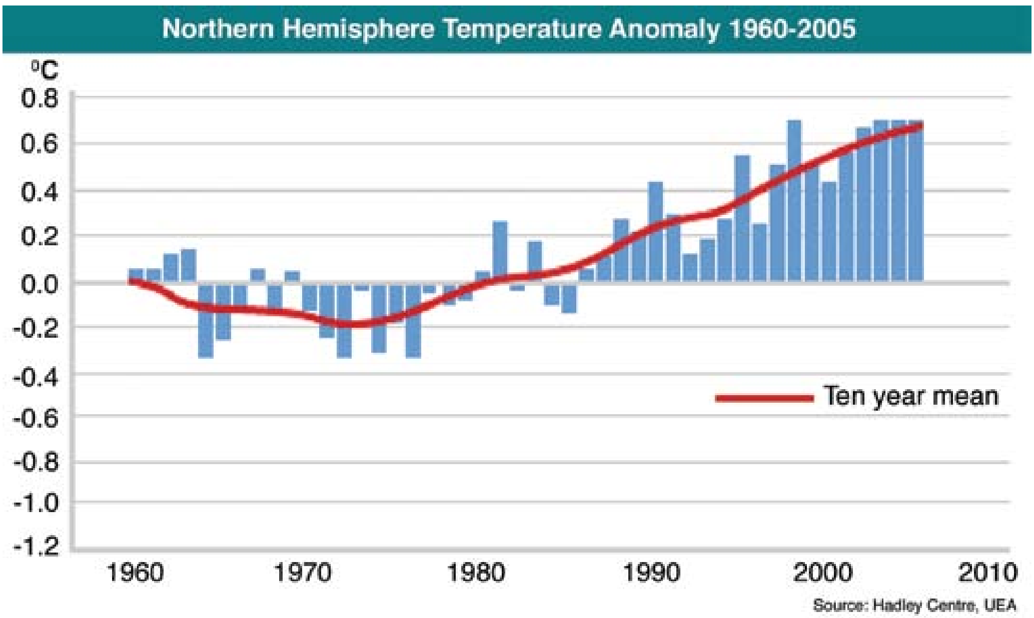
- Unfortunately direct management action is unlikely to prevent coral bleaching and mortality from climate change on most of the world's reefs.
- However, effective management can reduce the damage from direct human pressures and encourage the natural adaptation mechanisms to build up reef resilience;

- 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.

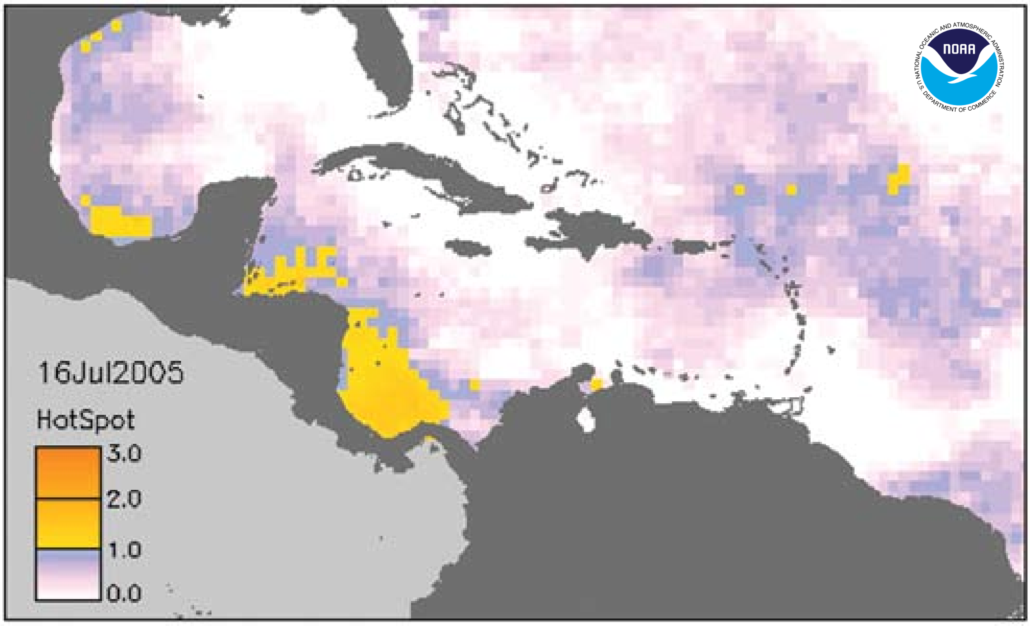
The 2005 bleaching event has followed a long, slow decline in the status of Caribbean coral reefs over thousands of years; especially during the last 50 years. Many Caribbean reefs have lost up to 80% of their coral cover during this time. The causes included climate related factors prior to 2005, but 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.



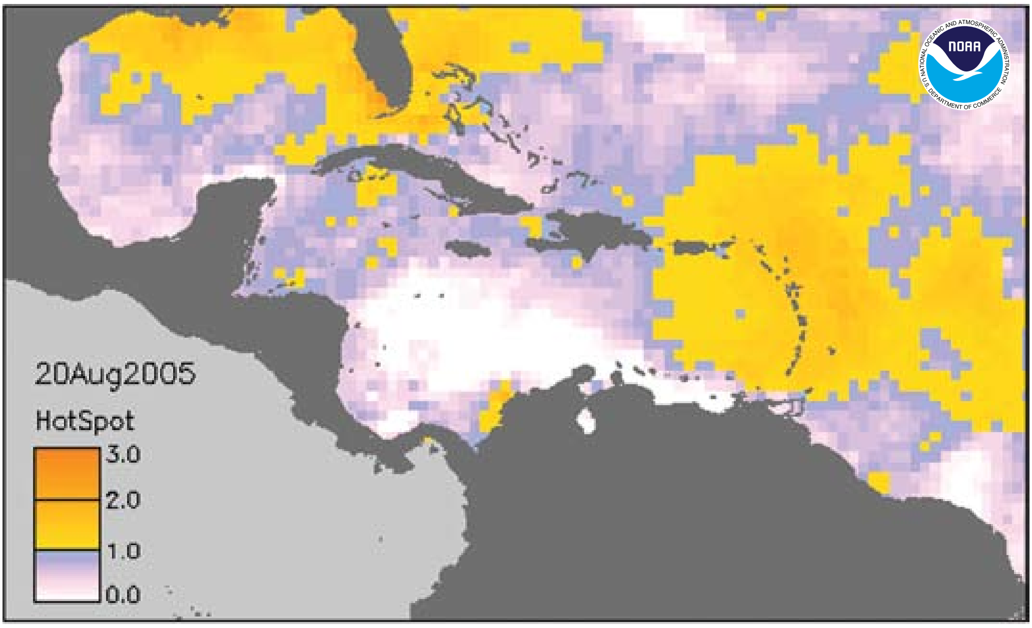
This 1st figure illustrates a typical HotSpot image (explanation on p. 38) that was generated from satellite data and distributed throughout the Wider Caribbean. The HotSpot on 16 July 2005 shows waters 1ºC to 2ºC above the normal summer maximum as seen as 'warm' yellow and orange colors over central 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 30ºC. These waters then cooled and the corals recovered. By late June, surface waters exceeded 30ºC 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.

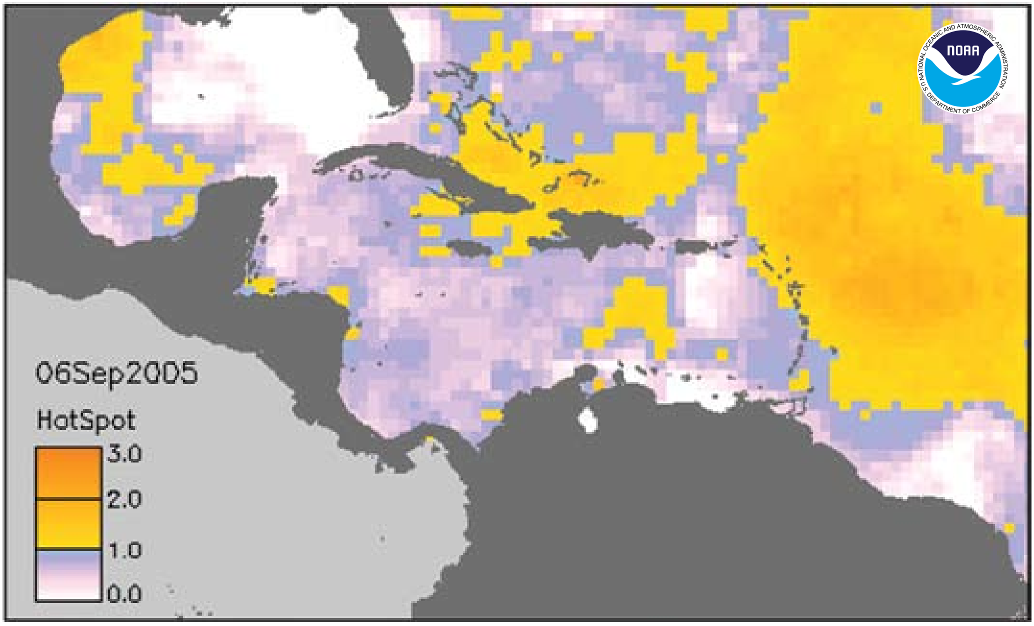
Although between 25% and 45% bleaching was reported in Belize and Mexico, the HotSpot along the Mesoamerican Reef system dissipated with the regular passage of storms during 2005, which prevented any significant bleaching related mortality. Despite the cooling benefits to the region, Hurricanes Wilma 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 2ºC to 3ºC 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.

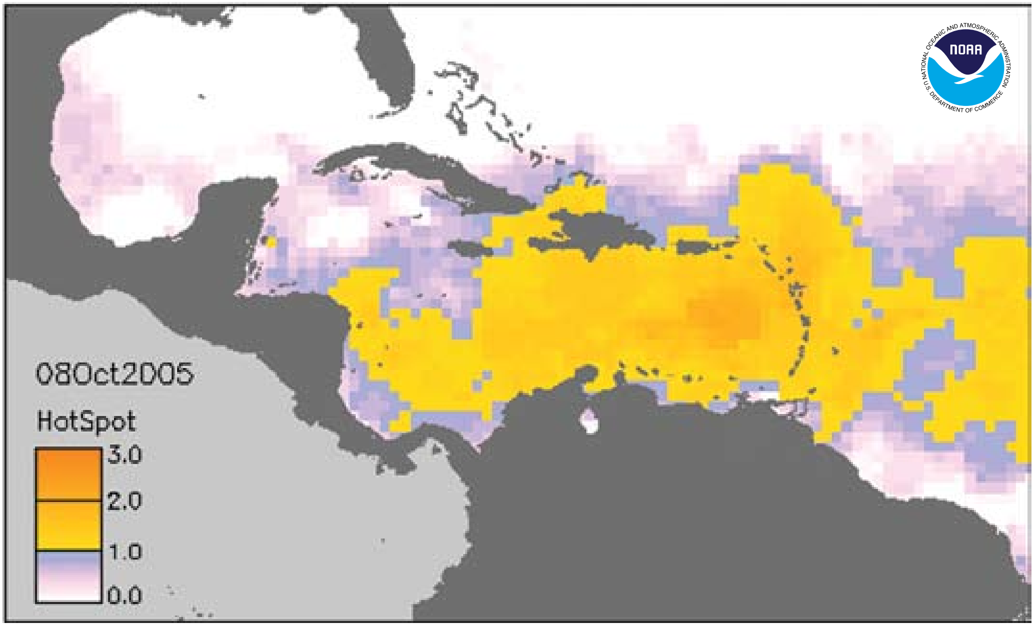
By early August, concern was growing that bleaching would damage the reefs of Florida and the Gulf of Mexico. As the HotSpot expanded in the north, there were reports of extensive bleaching in the Florida Keys, with water temperatures around 31°C and almost totally calm and sunny conditions. In late 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 2ºC to 3ºC 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 CO_2 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 grown 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.

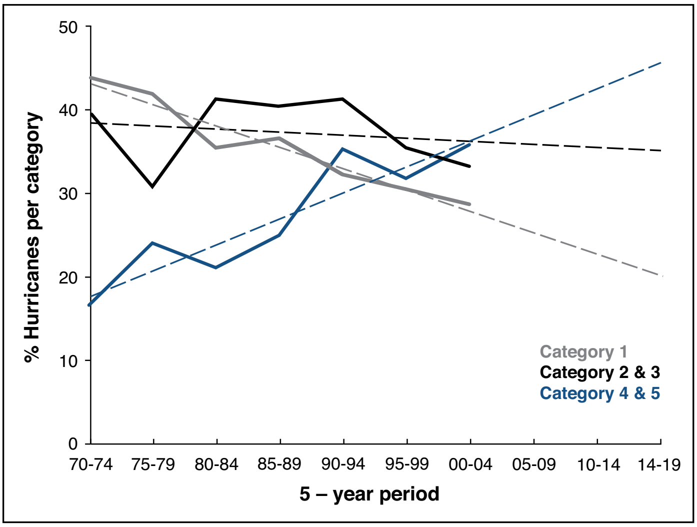
The report guides reef managers into steps they can take at national and global levels to raise awareness of the potential devastation that increasing global climate change, though the release of greenhouse gases, can have on coral reefs. However, the emphasis is on providing managers with practical 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 4.0ºC 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 CO^2 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 CO_2 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.