PACIFIC BLUE FOUNDATION
Sustaining Reef Communities

2010

Annual Report

The Pacific Blue Foundation (PBF) provides basic research, education, encouragement and implementation of sustainable practices in coastal regions with the ultimate goal of preserving and promoting the biological and cultural diversity of the region.

2010 Annual Report

Pacific Blue Foundation focused on a number of cultural projects in 2010, many of which were also closely connected to the organization's environmental and educational goals of conservation and empowerment. Pacific Blue Foundation recognizes that culture, education and ecology are closely intertwined, with the development of each supporting the progress of the other.

Tradition continually proves to be valuable to conservation efforts, promoting practices that are generally sustainable and respected as a source of local knowledge that has served communities for generations. Local customs often revered the environment and its natural resources, recognizing the community's dependence on surrounding ecosystems. By embracing the strength of the culture, educating individuals on the impact they have on the environment, and demonstrating how it can affect their own livelihoods, the organization hopes to enable local communities to sustainably manage their fisheries and economy, while also protecting coastal ecology and traditions alike. Instead of viewing culture as a relic from the past, Pacific Blue Foundation celebrates customs for their application and effectiveness in the present.

Pacific Blue Foundation has also continued research on coral reef conservation, branching out this year to encompass studies not only in shallow reefs but in deep sea environments as well. Preserving these delicate corals depends on communities to take an active part in protecting the health of the coral reefs, an ecosystem that bears such a large biodiversity that they demand our utmost attention.

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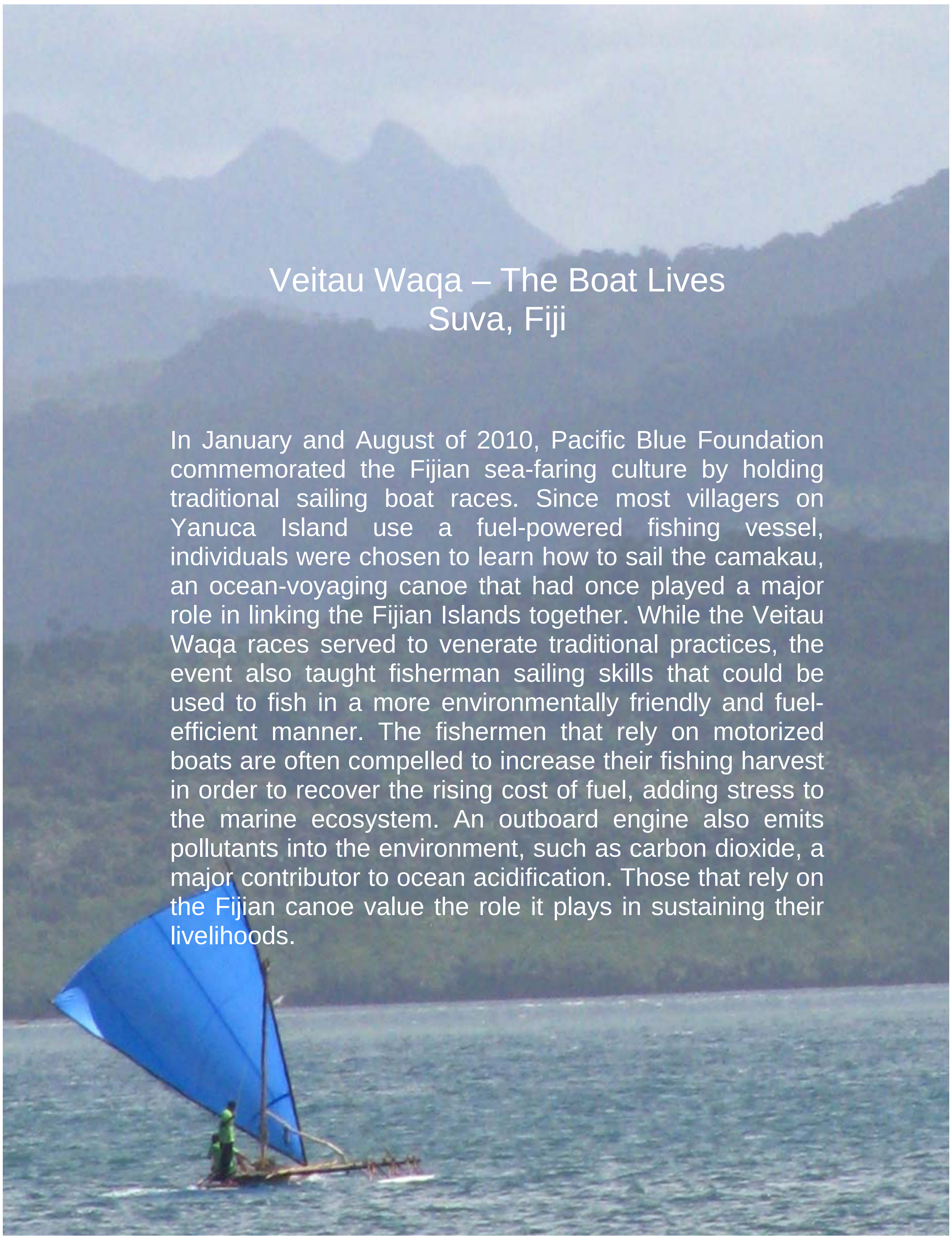
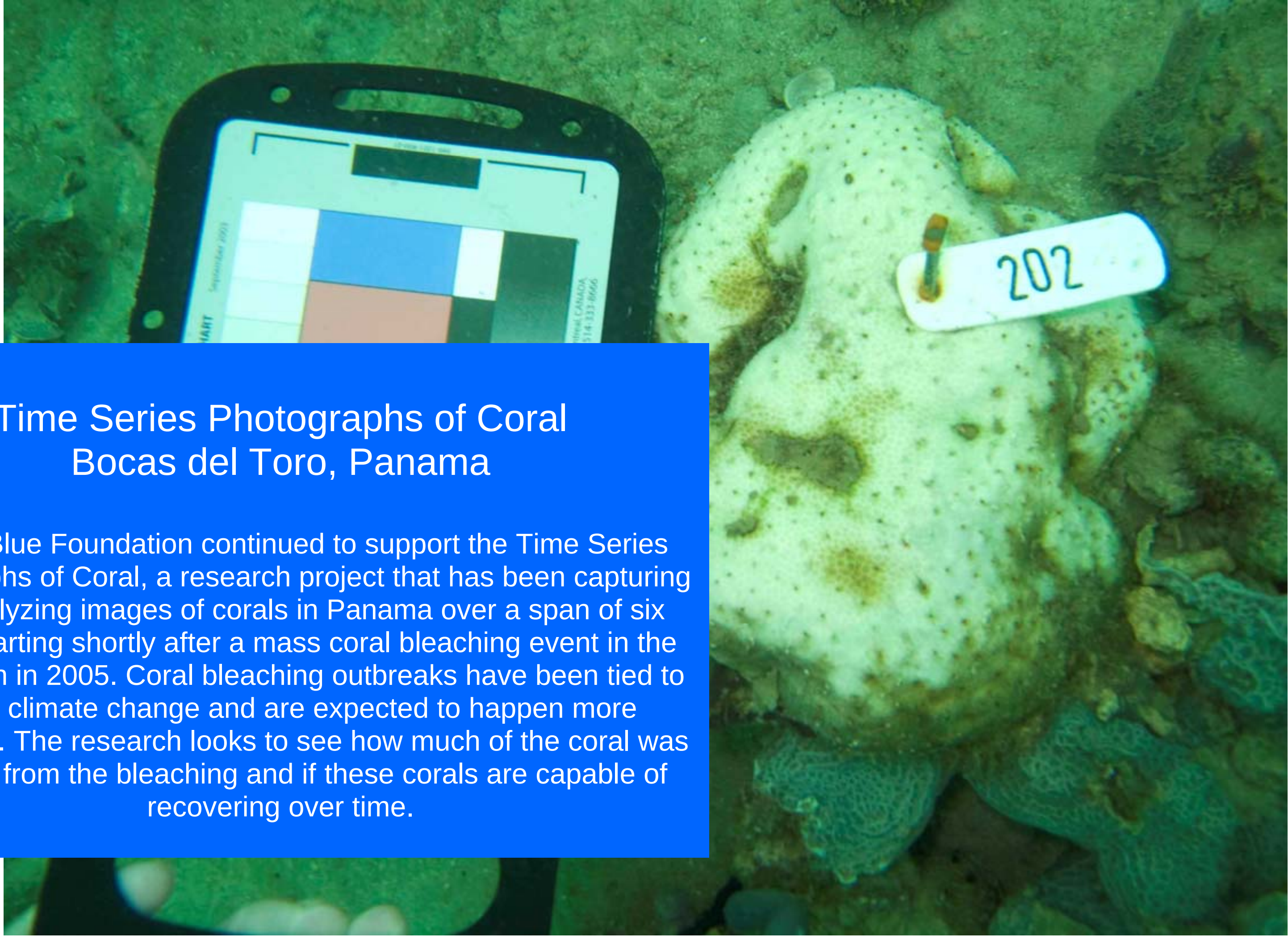
Highlights

Pacific Blue Foundation was excited to be involved in a number of projects in 2010. The organization funded research and implemented programs ranging from ocean acidification work in Australia to the revival of the Fijian canoe in Suva, Fiji.



Veitau Waqa – The Boat Lives
Suva, Fiji

In January and August of 2010, Pacific Blue Foundation commemorated the Fijian sea-faring culture by holding traditional sailing boat races. Since most villagers on Yanuca Island use a fuel-powered fishing vessel, individuals were chosen to learn how to sail the camakau, an ocean-voyaging canoe that had once played a major role in linking the Fijian Islands together. While the Veitau Waqa races served to venerate traditional practices, the event also taught fisherman sailing skills that could be used to fish in a more environmentally friendly and fuel-efficient manner. The fishermen that rely on motorized boats are often compelled to increase their fishing harvest in order to recover the rising cost of fuel, adding stress to the marine ecosystem. An outboard engine also emits pollutants into the environment, such as carbon dioxide, a major contributor to ocean acidification. Those that rely on the Fijian canoe value the role it plays in sustaining their livelihoods.



Time Series Photographs of Coral
Bocas del Toro, Panama

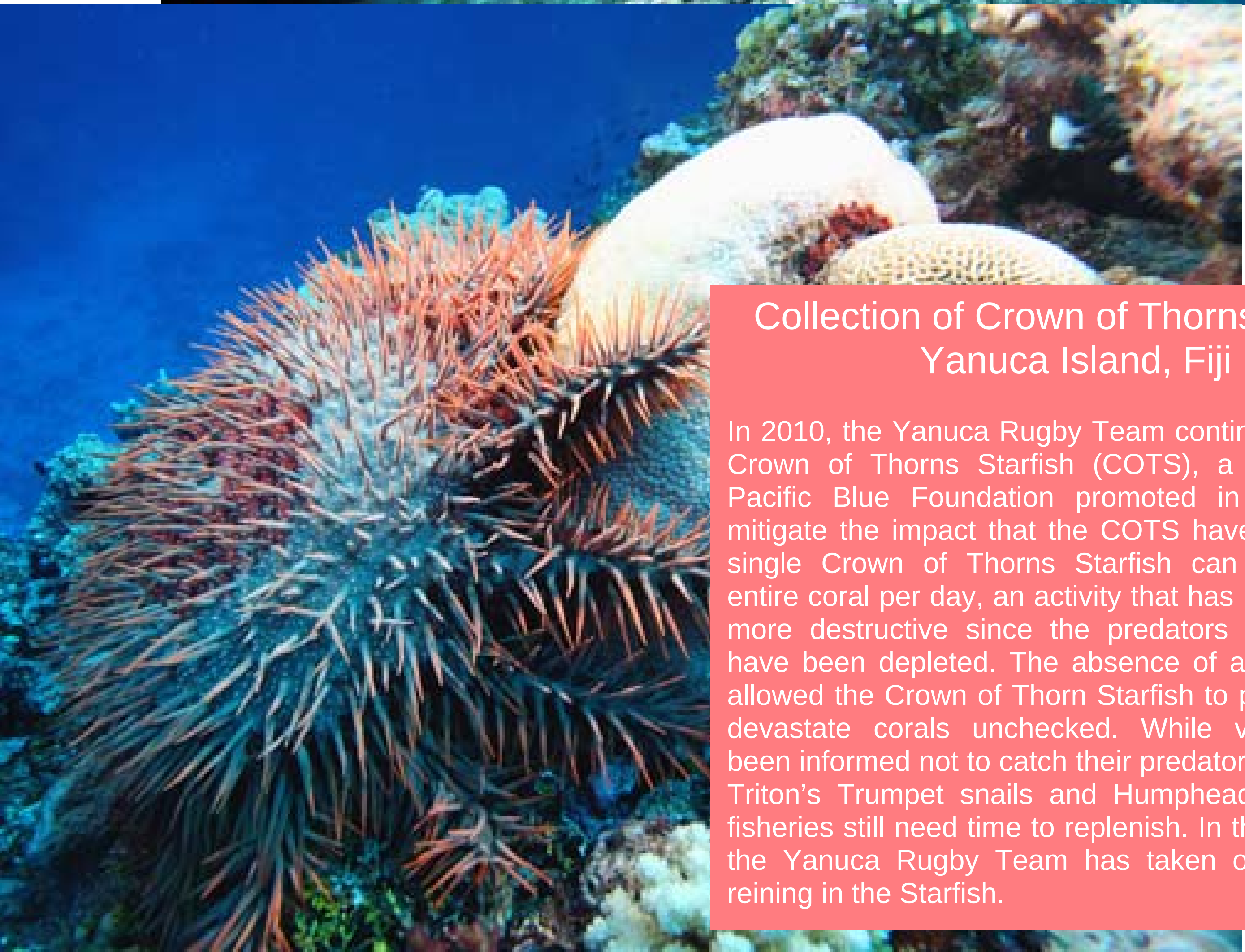
Pacific Blue Foundation continued to support the Time Series Photographs of Coral, a research project that has been capturing and analyzing images of corals in Panama over a span of six years, starting shortly after a mass coral bleaching event in the Caribbean in 2005. Coral bleaching outbreaks have been tied to global climate change and are expected to happen more frequently. The research looks to see how much of the coral was affected from the bleaching and if these corals are capable of recovering over time.

CP-FOCE
Heron Island, Australia

Carbon emissions are on the rise and the ocean has become a huge carbon sink, absorbing at least a third of man-made carbon dioxide. This chemical change is increasing the ocean’s acidity, thereby impeding the ability of some sea life, including coral reefs, to calcify and grow. In 2010, Pacific Blue Foundation continued to fund ocean acidification research on Heron Island using the Coral Proto – Free Ocean Carbon Enrichment System. The system infuses the water around specified corals with carbon dioxide, allowing researchers to study how increased levels of dissolved carbon dioxide will impact coral reefs.

Mesophotic Coral Research
Coral Sea Conservation Zone, Australia

Global climate change will likely have a devastating effect on coral reefs, but it is possible that rising temperatures will not have as extensive an impact on deeper corals. An increase in storm frequency and intensity has left many shallow reefs destroyed with little hope of recovery before the next onslaught of storms. Scientists are beginning to question whether coral have a better chance of surviving in a mesophotic reef, where coral do not face the same disturbances as their shallow-dwelling brethren. Pacific Blue Foundation began to fund research of Mesophotic Coral Ecosystems, or corals that habitat deeper waters – 30 meters to 150 meters deep – in order to determine if deeper waters will provide coral with some means of protection from climate change.



Collection of Crown of Thorns Starfish
Yanuca Island, Fiji

In 2010, the Yanuca Rugby Team continued to collect Crown of Thorns Starfish (COTS), a program that Pacific Blue Foundation promoted in an effort to mitigate the impact that the COTS have on coral. A single Crown of Thorns Starfish can consume an entire coral per day, an activity that has become much more destructive since the predators of the COTS have been depleted. The absence of a predator has allowed the Crown of Thorn Starfish to proliferate and devastate corals unchecked. While villagers have been informed not to catch their predators, such as the Triton's Trumpet snails and Humphead wrasse, the fisheries still need time to replenish. In the mean time, the Yanuca Rugby Team has taken on the role of reining in the Starfish.

Pre-Colonial Fijian Music

A majority of Fijian history has not been written down, having been predominantly passed down orally, with music being one of the main methods of imparting traditional knowledge. Unfortunately, Fijian traditional music and culture is fading from the forefront of Fijian lifestyles as modern practices take precedence in Fiji. Fijians would traditionally take on different tasks, with each contribution an essential part of the communal meal that the village would enjoy together. Unfortunately, with dwindling resources, individuals must put more effort into obtaining food, whether fishing or taking up a trade that will provide them with money to purchase food, and emphasis is no longer placed on performing Meke for a living, a ceremony with song and dance that conveys a story. Pacific Blue Foundation sponsored two Doctorate students, Tiffany DuMouchelle and Stephen Solook, to research the history of traditional Fijian music. They worked closely with the Ministry of Fijian Affairs Institute of Language and Culture to document the songs, stories, and chants performed by Fijians. The Ministry currently only has a handful of people throughout the country collecting and documenting this information, and willingly supported the research. They helped Pacific Blue Foundation access different places and people, obtain permission to visit certain villages and provided the students with translators when they could. DuMouchelle and Solook researched documents from the Fijian Archives, museums, universities and government agencies, recognizing that a majority of the most detailed collections of pre-colonial music have not left Fiji. There are instruments in the Fiji Museum that are no longer played, such as the Panpipes, and many that are on the brink of being lost, such as the nose flute. Fortunately, the two researchers were able to meet and interview Kaveni Tamani, one of the last known nose-flute players in the world.

Taoba Project
Totoya Island, Fiji

Pacific Blue Foundation successfully completed a poverty alleviation project in 2010. The project began in 2009 after members of the organization met a special-needs boy named Taoba. A lack of funds prevented Taoba’s family from providing an ideal space to suit the child’s condition. The work was dubbed the Taoba Project, with Pacific Blue Foundation and Totoya villagers working together to create a safe environment for Taoba and ensure that he could continue to live at home with his family. The Taoba Project was jointly funded by Pacific Blue Foundation and a grant from the Department of Social Welfare in Fiji.

Projects, Research & Funding

Panama

Bocas Del Toro

Funding for Time Series Photographs & Coral Reef Analysis

- Dr. David Kline with the University of Queensland with Pacific Blue Foundation Sponsorship

Australia

Heron Island

Funding for Ocean Acidification Research with CP-FOCE system

- Dr. David Kline with Pacific Blue Foundation Sponsorship

Coral Sea Conservation Zone

Funding for Mesophotic Coral Ecosystem Research

- Dr. Kline, Dr. Bongaerts and Tom Bridge with Pacific Blue Foundation Sponsorship

Fiji

Suva Island

Veitau Waqa Traditional Canoe Races & Training of locals to sail Camakau

- Pacific Blue Foundation Sponsorship

Funding and Completion of Carpenty Course for villager, Jim Makoto

- Pacific Blue Foundation Sponsorship

Research of Pre-Colonial Fijian Music with Ministry of Fijian Affairs

- Tiffany DuMouchelle and Steven Solook with Pacific Blue Foundation Sponsorship

Totoya Island

Cultural Event with Roko Sau and wife visiting home islands of Totoya and Vanuavatu

- Pacific Blue Foundation Sponsorship

Funding and Completion of Poverty Alleviation "Taoba" Project

- Pacific Blue Foundation Sponsorship

Yanuca Island

Control Program for Crown of Thorns Starfish

- Yanuca Rugby Team with Pacific Blue Foundation Sponsorship

Education Funding for Five Tertiary Students

- Pacific Blue Foundation Sponsorship

Attendance of FLMMA Workshop by leaders of Yanuca Community

- Pacific Blue Foundation Sponsorship

Support of PCDF Annual Biology Monitoring Survey on Yanuca Waters

- Pacific Blue Foundation Sponsorship

Six-Week Training Program in Suva attended by two Kindergarten Teachers

- Pacific Blue Foundation Sponsorship

Publications
And
Scientific Literature

Caribbean Corals in Crisis: Record Thermal Stress, Bleaching, and Mortality in 2005

C. Mark Eakin[1*], Jessica A. Morgan[2], Scott F. Heron[3], Tyler B. Smith[4], Gang Liu[2], Lorenzo Alvarez-Filip[5], Bart Baca[6], Erich Bartels[7], Carolina Bastidas[8], Claude Bouchon[9], Marilyn Brandt[10], Andy Bruckner[11], Lucy Bunkley-Williams[12], Andy Cameron[13], Billy D. Causey[14], Mark Chiappone[15], Tyler R.L. Christensen[2], M. James C. Crabbe[16], Owen Day[17], Elena de la Guardia[18], Guillermo Díaz-Pulido[19], Daniel DiResta[20], Diego L. Gil-Agudelo[21], Dave Gilliam[22], Robert Ginsburg[10], Shannon Gore[23], Hector M. Guzman[24], James C. Hendee[25], Edwin Hernández-Delgado[26], Ellen Husain[27], Christopher F.G. Jeffrey[28], Ross J. Jones[29], Eric Jordán-Dahlgren[30], Les Kaufman[31], David Kline[32], Phil Kramer[33], Judith C. Lang[34], Diego Lirman[10], Jennie Mallela[35], Carrie Manfrino[36], Jean-Philippe Maréchal[37], Ken Marks[34], Jennifer Mihaly[38], W. Jeff Miller[39], Erich M. Mueller[40], Erinn Muller[41], Carlos A. Orozco Toro[42], Hazel A. Oxenford[43], Daniel Ponce-Taylor[13], Norman Quinn[44], Kim B. Ritchie[7], Sebastián Rodríguez[8], Alberto Rodríguez Ramírez[21], Sandra Romano[4], Jameal F. Samhouri[45], Juan A. Sánchez[46], George P. Schmahl[47], Burton Shank[31], William J. Skirving[3], Sascha C.C. Steiner[48], Estrella Villamizar[49], Sheila M. Walsh[50], Cory Walter[7], Ernesto Weil[51], Ernest H. Williams[12], Kimberly Woody[28], and Yusri Yusuf[52]

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Abstract (235 words, request NTE 250-300 words)

The rising temperature of the world's oceans has become a major threat to coral reefs through increasingly severe and frequent coral bleaching and mortality. In 2005, high ocean temperatures in the tropical Atlantic and Caribbean resulted in the most extensive bleaching event recorded in the basin. Thermal stress monitored using satellite data exceeded any observed in 20 years of satellite data from the Caribbean, and regionally-averaged temperatures were the warmest in over 150 years. Satellite-based tools warned coral reef managers and scientists of anomalous warm conditions in 2005 as they developed and spread across the greater Caribbean region, guiding both the timing and location of researchers' field observations. Collaborators from 22 countries undertook the most comprehensive documentation of basin-scale bleaching to date, finding over 80% of corals bleached and over 40% dead at many sites. Field surveys of bleaching and mortality exceeded prior efforts in detail and extent, and provide a new standard for documenting the effects of bleaching and for testing forecast products. Comparison of satellite data against field surveys demonstrated a significant predictive relationship between accumulated heat stress and bleaching intensity. The most severe bleaching coincided with waters nearest a western Atlantic warm pool that was centered off the northern end of the Lesser Antilles. This severe, widespread bleaching and mortality will undoubtedly have long-term consequences for reef ecosystems and suggests a troubled future for tropical marine ecosystems under a warming climate.

Introduction

Coral bleaching has become a major threat to coral reef ecosystems worldwide [1]. Bleaching occurs when stress to the coral-algal symbiosis causes loss of endosymbiotic algae (zooxanthellae) and, if prolonged or particularly severe, may result in partial or complete coral mortality [2]. While many sources of stress can cause corals to bleach, "mass" coral bleaching (at scales of 100 km or more) occurs when anomalously warm ocean temperatures, often coupled with high subsurface light levels, exceed corals' physiological tolerances. This was observed during recent major El Niño-Southern Oscillation events (*e.g.,* 1982-83 [3], 1997-98 [4], and 2002 [5]) and verified by laboratory experiments [6,7]. These bleaching events resulted in coral death, with impacts on reef habitats, structures and biodiversity lasting a decade or more [8,9].

From June to October 2005, a warm-water anomaly developed across the tropical Atlantic and greater Caribbean. Satellite-based sea surface temperature (SST) observations from the US National Oceanic and Atmospheric Administration (NOAA) [10] measured a large warming of ocean temperatures that reached a maximum value of 1.2 °C when averaged across all Caribbean reef sites. Elevated temperatures persisted for many weeks, possibly helping to fuel the most active Atlantic hurricane season on record [11] and causing the most severe and extensive mass coral bleaching event observed in the Caribbean.

NOAA's Coral Reef Watch (CRW) develops and maintains a suite of operational satellite-based products that provide coral bleaching nowcasts and alerts [10]. HotSpots are positive anomalies that reflect current thermal stress, while Degree Heating Weeks (DHWs) provide a measure of sustained thermal stress through the preceding 12-week period. NOAA warned coral reef managers and scientists of anomalous warm conditions as they developed and spread across the greater Caribbean region in 2005. The maps of thermal stress that can cause coral bleaching guided both the timing and location of researchers' field observations. As a result, collaborators from 22 countries undertook the most comprehensive documentation of basin-scale bleaching to date.

Results

NOAA measured thermal stress in 2005 that far exceeded thresholds [10] associated with the onset of mass coral bleaching (DHW = 4 °C-weeks) and mortality (DHW = 8 °C-weeks) (Figure 1A). As the event developed, water temperatures rose across the basin (Figure 2A, see below for explanation of symbols), resulting in a massive warm-water anomaly and cumulative thermal stress that exceeded 16 °C-weeks (Figures 1A, S1). Analysis of retrospective satellite data showed that the severe thermal stress in the Caribbean during 2005 was more intense than any of the previous 20 years (Figure 2B).

The timeline for the geographic spread of the 2005 Caribbean thermal stress can be decomposed into seven major phases as identified in Figure 2A: in late-May (i), thermal stress was observed off South America; by mid-June (ii), the Caribbean coast from Colombia to Nicaragua experienced elevated temperatures. In July (iii), warm anomalies persisted from Panama to Nicaragua and another region of warming developed east of the Antilles. Through August (iv), low-level stress was present across the basin; however, reefs in the Gulf of Mexico, Florida, the Bahamas, and the Lesser Antilles experienced high levels of stress. In September (v), the center of warming progressed along Cuba, Hispaniola, and Puerto Rico to the Leeward and Windward Islands while low-level stress persisted throughout the Caribbean. By October (vi), thermal stress had subsided in the

Gulf of Mexico; however, warm anomalies remained in the Windward Islands and affected the southern Caribbean. As the region of maximum warming moved southward during November (vii), waters around the northern Antilles cooled; low-level heat stress affected the northern coast of South America and subsequently dissipated [12].

After initial reports of bleaching in Colombia in June, CRW distributed alerts via the Internet as the thermal stress spread. Teams (represented by the many co-authors on this paper) deployed throughout the region to monitor the bleaching event as it developed, and subsequently to monitor coral mortality. Coral bleaching, infectious disease, and mortality extended across the entire Caribbean – bleaching was especially intense along the Antilles (Figure 1B), and was observed in most Caribbean coral species in depths to 40 m. Over 3600 field surveys were recorded from 28 jurisdictions (*i.e.*, states, territories) in 22 countries (Figure S2). After quality control, 2575 were used in the bleaching analysis and 1077 were used in mortality studies. Surveys were grouped by 0.5-degree pixel at twice-weekly time intervals to allow satellite data and field surveys to be analyzed at comparable scales.

Several species and sites were reported to bleach for the first time, including: the first known bleaching at Saba; the first documented mass bleaching of the Flower Garden Banks, including at least partial bleaching of all *Millepora alcicornis* and *Montastraea cavernosa* colonies; and the first reported mass bleaching of *Acropora palmata* in Virgin Islands National Park (VINP), a species recently listed as threatened under the US Endangered Species Act [13].

Surveys conducted from the peak of thermal stress through January 2007 were analyzed to assess coral mortality. Detailed and repeated monitoring revealed that a combination of bleaching and outbreaks of several diseases killed coral colonies stressed by high temperatures [12,14,15]. Some researchers identified continued mortality as late as October 2007 [15], beyond which it was difficult to attribute further mortalities to this bleaching event. In parts of the Caribbean, temperatures remained anomalously high during the boreal winter-spring and into mid-2006, although remaining below the bleaching threshold. Many corals remained bleached, and disease and mortality continued through much of 2006. Mortality exceeded 50% in several locations, making this the worst known case of thermal stress-related mortality in the Caribbean, and among the worst globally [16]. The record levels of thermal stress in 2005 were consistent with the pattern seen since the 1980s and 1990s in the Florida Keys, where thermal stress and bleaching were frequently followed by disease outbreaks in subsequent years [12].

In the Florida Keys in 2005, increased temperatures corresponded with a loss of resistance to disease and an increased abundance of coral pathogens in *A. palmata* [17], perhaps explaining the high incidence of disease following the thermal stress. In VINP, video surveys of permanent transects revealed that mortality occurred in colonies due to bleaching, and in colonies that became diseased either during bleaching, after recovery from bleaching, or without bleaching [14]. Frequent monitoring of *A. palmata* also revealed bleached corals suffered greater disease-associated mortality than unbleached colonies, indicating disease severity was dependent on host susceptibility [13]. In

Barbados, corals remained bleached for 8 months or longer before dying [18]; even a year after temperatures dropped below bleaching thresholds, corals remained bleached or pale at many sites, particularly within the important reef-builders of the *Montastraea annularis* species complex [19].

Comparison of satellite data with field surveys demonstrates a strong coherence between thermal stress and widespread bleaching (Figure 1B, 3A) and mortality (Figure 3B). Significant variability was seen in the severity of coral bleaching among reefs within each 0.5-degree satellite pixel, presumably due to variations in local conditions (*e.g.*, hydrodynamics, light, community composition). Consistent with CRW's previously established bleaching levels, significant coral bleaching began near 4 °C-weeks (Alert Level 1), with widespread mass bleaching and significant mortality occurring above 8 °C-weeks (Alert Level 2) [10]. However, bleaching also occurred at sites experiencing maximum stress levels below 4 °C-weeks, indicating that the 4 °C-weeks threshold may be somewhat conservative. Bleaching is also dependent on numerous local factors, including light level, temperature variability, and past thermal stress history [20]. Mortality was highest in jurisdictions in the north and central Lesser Antilles where stress exceeded 10 °C-weeks (Figure 1A).

At thermal stress levels less than 8 °C-weeks, significant levels of mortality were rare (4 of 143 surveys, <3%; Figure 3B). At and above this threshold, significant mortality was observed in 31% of events. Local conditions may have interacted with large-scale warming to reduce the effect of the thermal stress (*e.g.*, coral community structure, small-scale hydrodynamics, past bleaching; the analysis of which is beyond the scope of this meta-analysis). All of this suggested that 8 °C-weeks is a conservative predictor that should be weighed carefully by reef managers – below the 8 °C-weeks threshold significant mortality generally is not expected, and above it an ecologically important 1-in-3 risk of mortality existed during this event. The slow rate of recovery seen in Caribbean reefs [16,21] suggests that such levels of mortality may decide the fate of coral reef ecosystems in this region.

Discussion

Unlike many past Caribbean bleaching years, strong tropical climate patterns were only a minor driver of Caribbean SSTs in 2005. Analysis of temperature anomalies across the tropical North Atlantic indicated that much of the warming (0.45 °C of the 0.9 °C anomaly *vs.* a 1901-1970 baseline) was attributable to monotonic climate change, while only 0.2 °C was attributable to the weak 2004-05 El Niño, and even less of the anomaly was attributable to the Atlantic Multi-decadal Oscillation (< 0.1 °C) [22]. Despite the lack of strong tropical forcing, 2005 stands among the warmest years on record [11]. NOAA Extended Reconstructed SSTs [23,24] showed that average ocean temperatures during the July-October period for the Caribbean exceeded temperatures seen at any time during the past 154 years (Figure 4). Anticipated future warming of ocean waters [25] is expected to increase the likelihood of future Caribbean bleaching events [26].

High ocean temperature also contributed to the record 2005 hurricane season [22] that damaged coral reefs in Jamaica, Cuba, the Yucatan, Flower Garden Banks, and the Florida Keys [12]. Hurricanes can cause mechanical damage to coral reefs, from sloughing of coral tissue to dislodgement of colonies, with potential effects of reduced recovery following bleaching and long-term ecosystem decline [12]. However, hurricanes that pass within several hundred km of coral reefs can cool anomalously warm SSTs below bleaching thresholds, and were probably significant in reducing thermal stress and preventing more severe bleaching in the Florida Keys in 2005 [12,27]. The absence of such cooling by tropical storms in the Leeward Islands (Figure S3) contributed to the extreme warming, bleaching, and mortality. Figure 2A shows that the major hurricanes of 2005 (**D**ennis, **E**mily, **K**atrina, **R**ita, **W**ilma) were strong enough to reduce the Caribbean-average HotSpots.

Many Caribbean reefs look very different from reefs of the early 20th century due to a wide array of human disturbances [28,29]. Natural climate variability is unlikely to be the cause of declines in Caribbean reefs over recent decades, as coral reef community composition had remained remarkably stable for 220,000 years [30]. The increase in coral bleaching is strongly attributable to anthropogenic climate change [1] and is likely to be an even greater threat to coral reefs in the future [26,31]. The mass bleaching and mortality from the 2005 warming has further disturbed Caribbean ecosystems that were already under assault [12,29].

Mass coral bleaching from thermal stress, followed by disease outbreaks [32], has become a threat common to coral reefs globally. Bleaching and mortality at levels reached in the Caribbean in 2005 will undoubtedly have long-term consequences for coral reefs. Data such as these will aid researchers and resource managers as they develop actions to protect reefs against the thermal stress anticipated in coming decades [33]. As global ocean temperatures continue to rise, managers will have to take concerted efforts to enhance the resilience of coral reefs and prevent dramatic declines in valuable coral reef resources.

Materials and Methods

NOAA Coral Reef Watch (CRW) thermal stress products are based on nighttime-only Advanced Very High Resolution Radiometer (AVHRR) sea surface temperatures (SST) from operational NOAA polar-orbiting satellites and are produced in near-real-time at 0.5-degree (50-km) spatial resolution. SST anomalies compare the measured temperature with the expected value at that time of year for every location. HotSpots are positive anomalies above the mean temperature of the climatologically warmest month at each satellite pixel. Degree Heating Weeks (DHWs) accumulate HotSpot values that are greater than or equal to 1°C over the preceding 12-week period [10]. The satellite-derived quantities calculated for this paper at each data pixel included: date of first issuance of Bleaching Watch alert (HotSpot > 0°C); value of maximum DHW (°C-weeks); date of No Stress alert (HotSpot = 0).

The DHW map (Figure 1A) includes values in coastal regions that are masked in the current operational CRW products. For display in this figure, the coastal values were inferred using kriging, a common statistical technique. However, for the subsequent analysis (Figure 2A) and comparison with field data (Figure 3), only data values retrieved from the operational data were used. Spatial averaging of satellite metrics (Figure 2A, S1) was performed using operational data from greater Caribbean pixels containing, or nearest to, coral reef locations within the region [100W-55W, 5N-35N].

CRW operational products were first available on 12-Sep-2000. The 22-year time series of annual maximum DHW (Figure 2B) was produced from a retrospective dataset that emulated the CRW near-real-time operational product [1] for the period 1985-2006 using data from the Pathfinder Version 5.0 dataset [34]. Spatial averaging was undertaken using the same pixels used for the operational data.

Field surveys of coral bleaching and mortality included at least the following quantitative data: 1) measures of coral bleaching as coral cover bleached (%), number of coral colonies bleached (*n*) and total number of colonies surveyed (*N*), or both; and/or 2) measures of coral mortality from bleaching and disease incidence as coral cover dead (%), number of coral colonies dead (*n*) and total number of colonies surveyed (*N*), or both; 3) average observation depth (m); 4) observation date; and 5) observation location, including latitude, longitude, and reef site name. Data were quality controlled to exclude observations that met any of the following criteria: 1) bleaching observations taken before the onset of thermal stress (1st Bleaching Watch); 2) bleaching observations taken after subsidence of thermal stress, defined as the 90th day following the date that the last No Stress alert was issued in 2005; and 3) mortality observations taken before the maximum DHW value occurred in 2005. Multiple observations (quadrats or transects) from the same reef site on the same date and depth (± 5 m) were combined as either means of percent cover data or proportion of the number of colonies surveyed. The 2575 bleaching surveys used in this analysis (Table S1) span the period 3-Jun-2005 through 13-Feb-2006. The 1077 mortality surveys used to estimate mortality associated with the thermal stress event were conducted during 25-Jul-05 to 20-Jan-2007.

As the multiple researchers taking part in this paper used a variety of methods, the work presented here is a meta-analysis. The techniques used are all highly comparable, well-accepted field methods. The authors assume that differences among techniques were randomly distributed with respect to thermal stress. Past comparisons among coral reef survey methods have demonstrated that while there are some biases among methods, most provide comparable results when comparing among similar data such as percent coral cover or disturbance [35,36]. It is important to note that the percentage of colonies bleached is often higher than the percentage of cover bleached because (1) small colonies bleached more often than large colonies; and/or (2) both partially- and wholly-bleached colonies were counted in some survey methodologies. However, a comparison of the linear regressions of percent cover bleached and percent colonies bleached with thermal stress (Figure S4) indicate no significant differences in the slopes of each parameter (cover = 3.91 ± 0.89 [slope ± 95% confidence interval] vs. colonies = 3.43 ± 0.70). This supports the assumption that the methods provided comparable results for this meta-analysis. Also, because any visible bleaching typically indicates a loss of most of the zooxanthellae originally present [37], it is appropriate to include any degree of bleaching, from pale and partially bleached to fully bleached colonies, as a sign of stress response. The same applies to partial and complete mortality as either indicates a response to thermal stress through bleaching or disease mortality. Therefore, partial and complete bleaching and partial and complete mortality of corals were combined in this analysis. Mortality data included recent mortality only as determined by expert observers; however, the cause of mortality was not always identifiable. Data from all sites and surveys are combined in this study as we were testing for differences among surveys at different thermal stress, not for spatial or temporal patterns. An analysis of reefs in the region showed that 4% recent partial mortality exists as a background level during surveys in the absence of major disturbance [38].

Operational satellite products from the co-located (or next-nearest) satellite pixel were compared with all field observations (Figure S2). Figure 3A shows linear regression of mean coral bleaching (combined cover and colonies datasets) compared with thermal stress as measured by the observed DHW at the time of the survey. For those surveys that occurred after the peak of thermal stress, the observed DHW may have declined from the maximum DHW, and therefore maximum thermal stress, experienced at that location. This can result in a level of bleaching greater than that expected from the observed DHW against which it is compared. Each data point represents the average of all surveys for a given 0.5-degree pixel conducted during the twice-weekly time period (temporal resolution) of the satellite data, plotted against the DHW value observed for that pixel and time period. The relationship between observed DHW and percent coral bleached was highly significant (*slope* = 3.41, *intercept* = 26.94, *DF* = 359, $p < 0.0001$, $r^2 = 0.24$). Given the variability of monitoring techniques employed, sampling errors within each technique, and local factors at individual reef sites (*e.g.*, shading, ponding), the explicative power of the satellite metric (r^2=0.24 for percent coral bleached) supports the relationship inferred between this thermal stress event and the observed bleaching.

Mortality data were considered only for observations after the peak of the thermal stress event (*i.e.*, the maximum DHW) within a pixel and were analyzed against the maximum thermal stress (Figure 3B). For this study, the threshold for significant mortality is defined where the observed value is twice the regional baseline mortality; *i.e.*, 8%. The nature of this analysis is very broad, combining field datasets across time, space, and survey methodology. No attempt was made to separate mortality induced by bleaching from that resulting by infectious disease as both are related to thermal stress [14,39]. The results show strong predictive power in the context of the greater Caribbean at the scale of 100s of km. However, thermal stress is far from a perfect predictor of mortality as local variability in the response of corals at and within individual reef sites is expected due to differences in circulation, shading, past thermal stress, and other factors that may confer local resilience.

Hurricanes extract heat from the upper ocean and induce vertical mixing. Both are mechanisms that can reduce the high temperatures of surface water which induces coral bleaching [12,27]. While 2005 was a record hurricane season, none passed near the

Lesser Antilles (Fig S3) where some of the highest bleaching and mortality were observed. Surface temperatures in this region remained above climatological values throughout the May-December period, with no respite from thermal stress (Fig 1A).

The NOAA Extended Reconstructed SST data [23,24] used in Figure 4 were averaged across reef-containing pixels (2-degree resolution) within the region [91W-55W, 5N-35N] and are presented as anomalies relative to the 1901-2000 mean.

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Figure Legends

Figure 1. Thermal stress and bleaching during the 2005 Caribbean bleaching event. (A) Maximum NOAA Coral Reef Watch Degree Heating Week (DHW) values showing the highest thermal stress recorded at each 0.5-degree pixel during 2005. Values of 4 °C-weeks typically result in significant bleaching; 8 °C-weeks typically result in widespread bleaching and significant mortality. (B) Jurisdictional means of coral bleached, by marker color and size, of percent live coral colonies (circles) and cover (diamonds).

Figure 2. Temporal patterns of thermal stress in the Caribbean. Average of satellite-derived thermal stress indices from the 0.5-degree pixels located nearest to reefs in the Caribbean (bounded by 35°N, 55°W, and the coast of the Americas). (A) NOAA coral bleaching HotSpots (purple) and DHW (red) in 2005. See text for explanations of (i)-

(vii). Letters D-W refer to the major hurricanes of 2005: **D**ennis, **E**mily, **K**atrina, **R**ita and **W**ilma. (B) Average of annual maximum thermal stress (DHW) values during 1985-2006. Significant coral bleaching was reported during periods with average thermal stress above 0.5, and was especially widespread in 1995, 1997-98, and 2005.

Figure 3. Mean coral bleaching and mortality versus thermal stress. (A) Small squares represent mean percent coral bleached for each 0.5-degree pixel and twice-weekly time period plotted against observed DHW value. Solid line indicates significant regression (*slope* = 3.41, *intercept* = 26.94, $DF = 359$, $p < 0.0001$, $r^2 = 0.24$). Colored bars indicate mean (grey bar) and standard deviation of all surveys (small squares) binned at 1 °C-week intervals; colors correspond to low bleaching risk (DHW < 4, blue), moderate risk (DHW ≥ 4, green), high bleaching and mortality risk (DHW ≥ 8, yellow), and very high risk (DHW ≥ 12, purple). (B) Triangles represent mean percent coral mortality (± standard deviation) plotted against the 2005 maximum DHW value recorded for each 0.5-degree pixel. Yellow and white areas correspond to inset box where values indicate number of data points in each quadrant (quadrants defined as 0 ≤ DHW < 8 and 0 ≤ mortality < 8%; 0 ≤ DHW < 8 and 8% ≤ mortality; 8 ≤ DHW and 0 ≤ mortality < 8%; 8 ≤ DHW and 8% ≤ mortality).

Figure 4. Long-term temperature trend in the Caribbean. Temperature anomalies for 2.0-degree reef pixels in the tropical Caribbean using NOAA Extended Reconstructed Sea Surface Temperature (ERSST). Anomalies plotted relative to 1901–2000. The dashed line shows the 2005 value.

Author Contributions: Conceived and designed the experiments: CME JAM SFH TBS GL TRLC WJS. Performed the experiments: TBS LAF BB EB CB CB MB AB LBW AC BDC MC MJCC OD EDLG GDP DD DLGA DG RG SG HMG JCH EHD EH CFGJ RJJ EJD LK DK PK JCL DL JM CM JPM KM JM WJM EMM EM CAOT HAO DPT NQ KBR SR ARR SR JFS JAS GPS BS SCCS EV SMW CW EW EHW KW YY. Analyzed the data: CME JAM SFH GL. Wrote the paper: CME JAM SFH TBS.

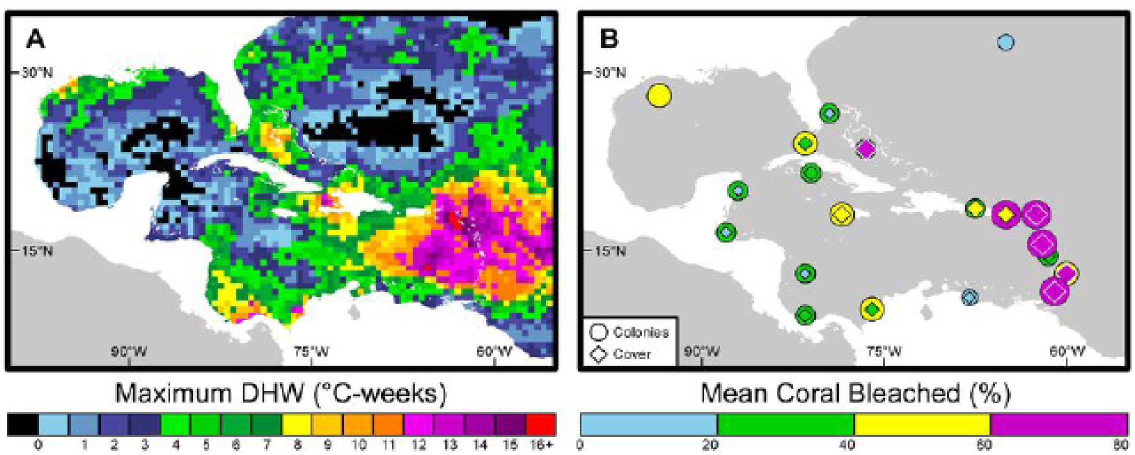
Figure S1. Sea surface temperature during the 2005 Caribbean bleaching event. Sea surface temperature (SST) averaged across the 0.5-degree pixels nearest Caribbean reef locations (bounded by 35°N, 55°W, 5°N and the coast of the Americas). The '+' symbols indicate the average climatological temperature during each month and the dashed line shows the maximum of these, an indication of the expected warmest (usually summer) temperature. The SST trace shows that, on average, temperatures around Caribbean reefs exceeded climatological values by close to 1°C for a period of more than four months. The magnitude and extended duration of the basin-wide thermal anomaly resulted in widespread coral bleaching and lowered the ability of corals to resist disease outbreak.

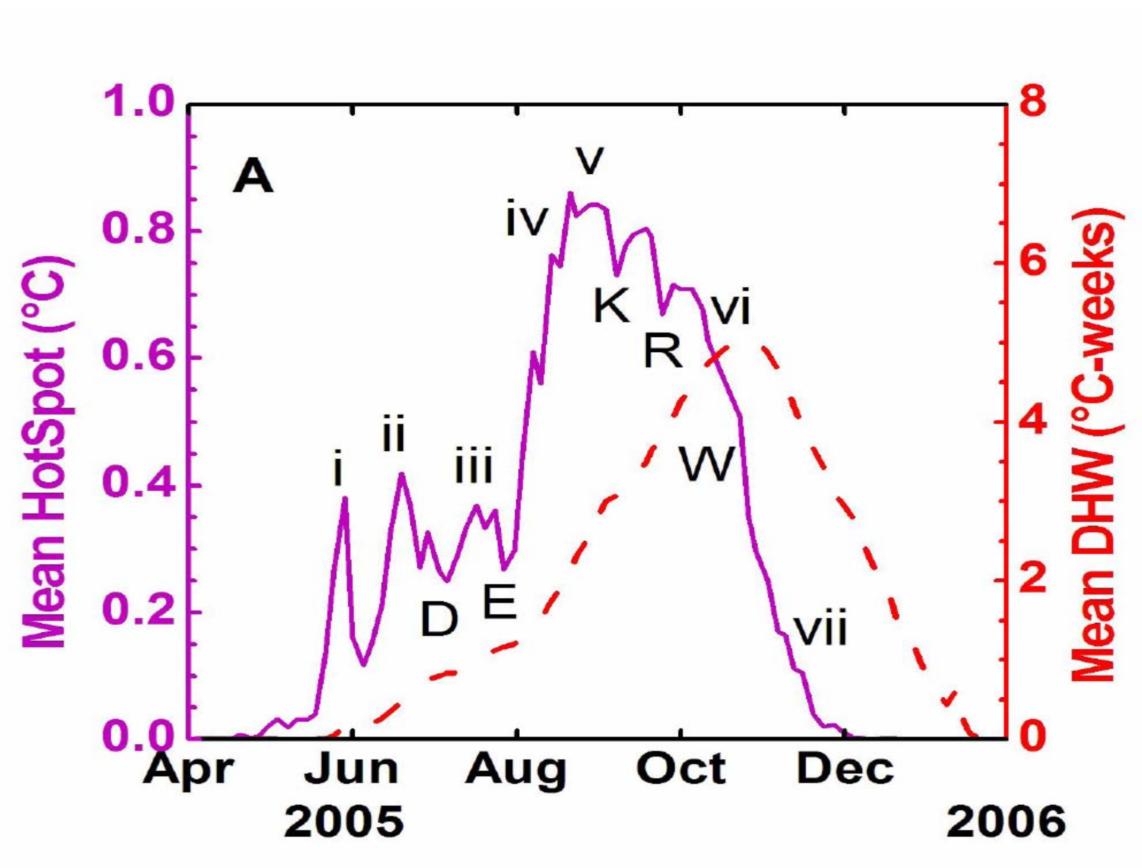
Figure S2. Locations of 2575 surveys from across the greater Caribbean region. Colors denote number of surveys at each of the 1212 sites. See Table S1 for location details.

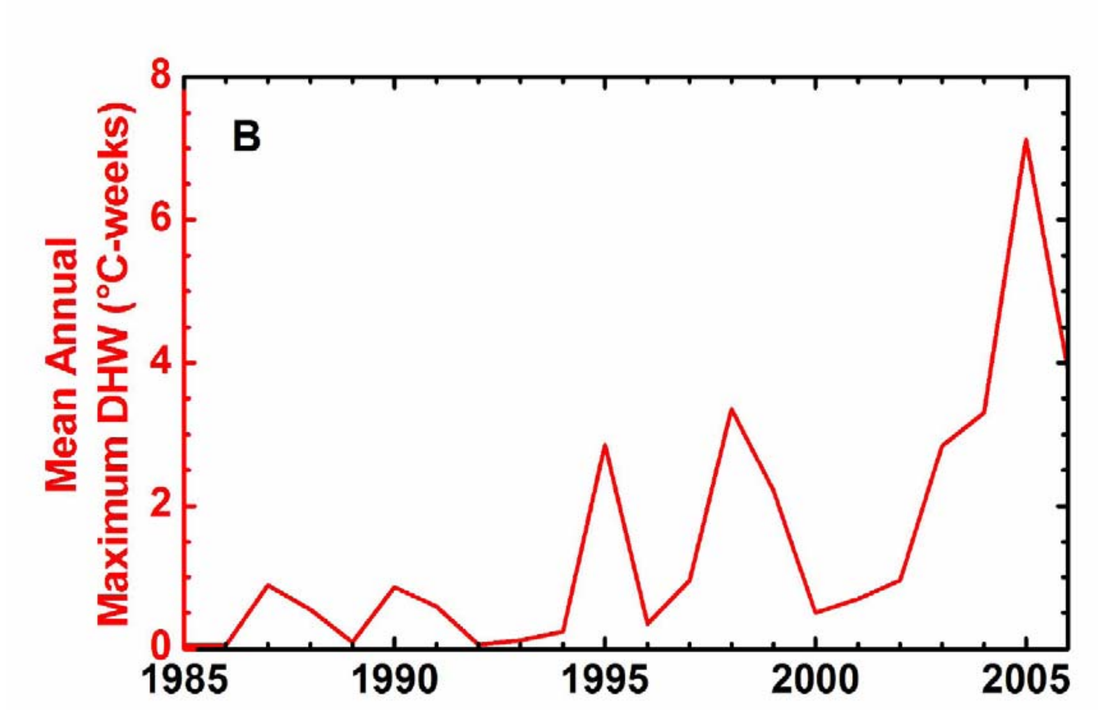
Figure S3. Thermal stress and hurricanes during the 2005 Caribbean bleaching event. Minimum observed SST anomaly for May-December 2005, overlaid with storm tracks (solid: hurricane, thickness denotes strength category; dotted: tropical storm; red: June-August; gray: September; black: October-December). Dates indicate initial date of hurricane formation. The large yellow region remained warmer than usual throughout this period.

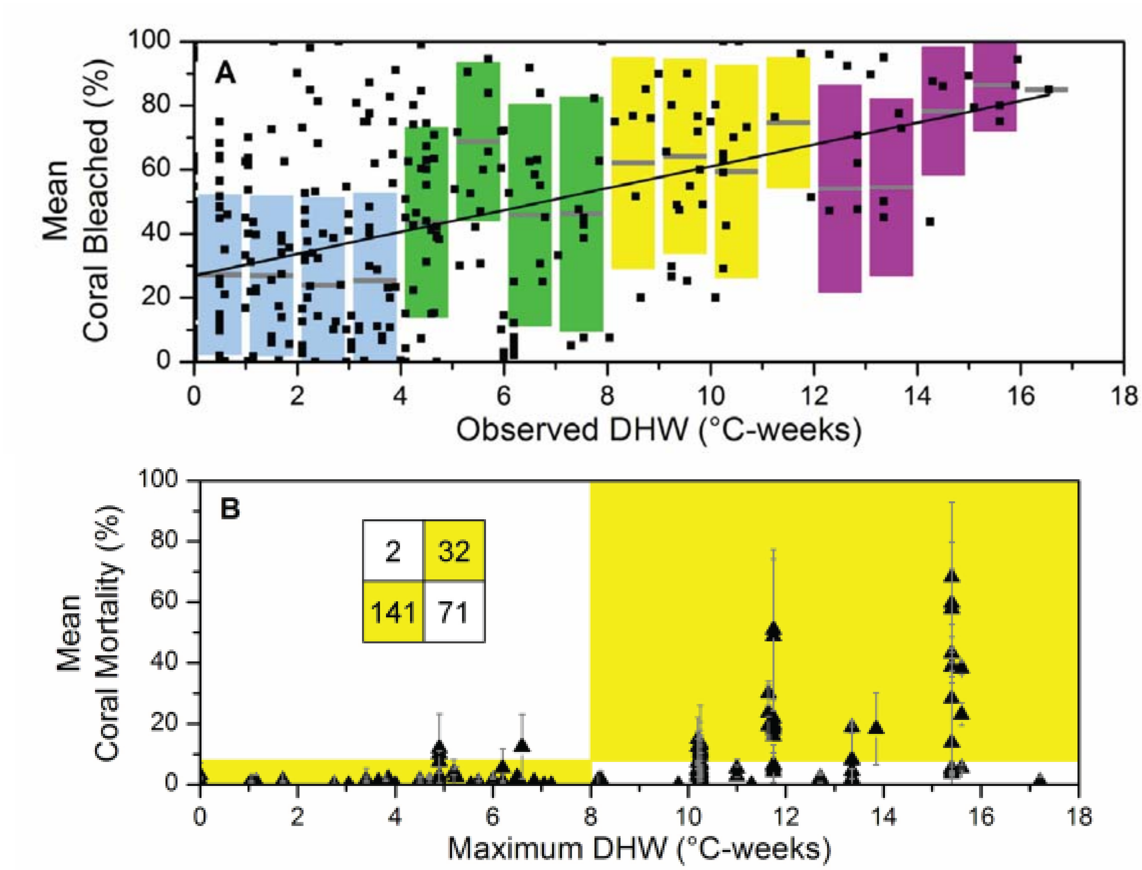
Figure S4. Comparison of bleaching survey methods. All observations of percent coral colonies (grey circles) and cover (black diamonds) are shown versus observed Degree Heating Week (DHW). Linear regressions for colonies (grey line) and cover (black line) are highly significant (cover *slope* = 3.91, *intercept* = 19.99, $DF = 212$, $p < 0.0001$, $r^2 = 0.26$; colonies *slope* = 3.43, *intercept* = 29.46, $DF = 304$, $p < 0.0001$, $r^2 = 0.24$) and indicate no difference in slopes, suggesting comparable results.

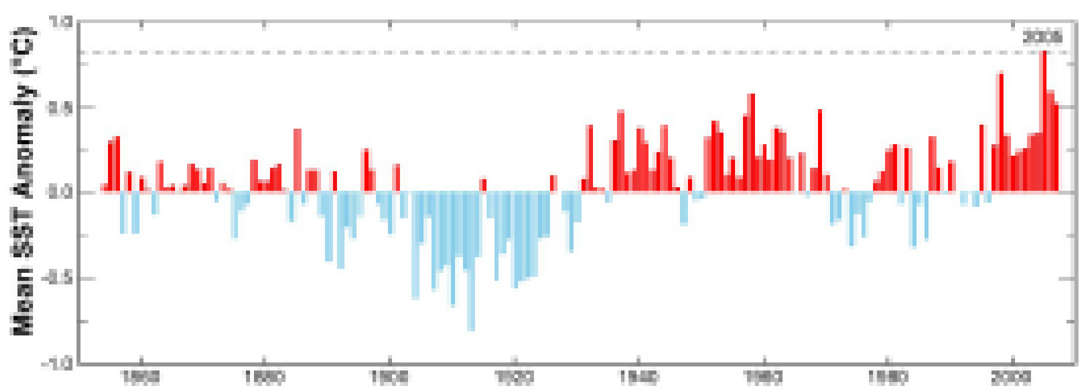
Table S1. Survey data used for analyses. Multiple observations from the same reef site, date and depth (± 5 m) were combined as either means of percent cover data or proportion of the number of colonies surveyed to provide 2575 bleaching surveys and 1077 mortality surveys.




A
Mean HotSpot (°C)
Mean DHW (°C-weeks)
i
ii
iii
iv
v
vi
vii
D
E
K
R
W
Apr
Jun
Aug
Oct
Dec
2005
2006
1.0
0.8
0.6
0.4
0.2
0.0
8
6
4
2
0


B
Mean Annual
Maximum DHW (°C-weeks)
8
6
4
2
0
1985
1990
1995
2000
2005


A
Mean
Coral Bleached (%)
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
Observed DHW (°C-weeks)
B
Mean
Coral Mortality (%)
2
32
141
71
Maximum DHW (°C-weeks)


Mean SST Anomaly (°C)
0.5
0.0
-0.5

Mesophotic coral ecosystems on the walls of Coral Sea atolls

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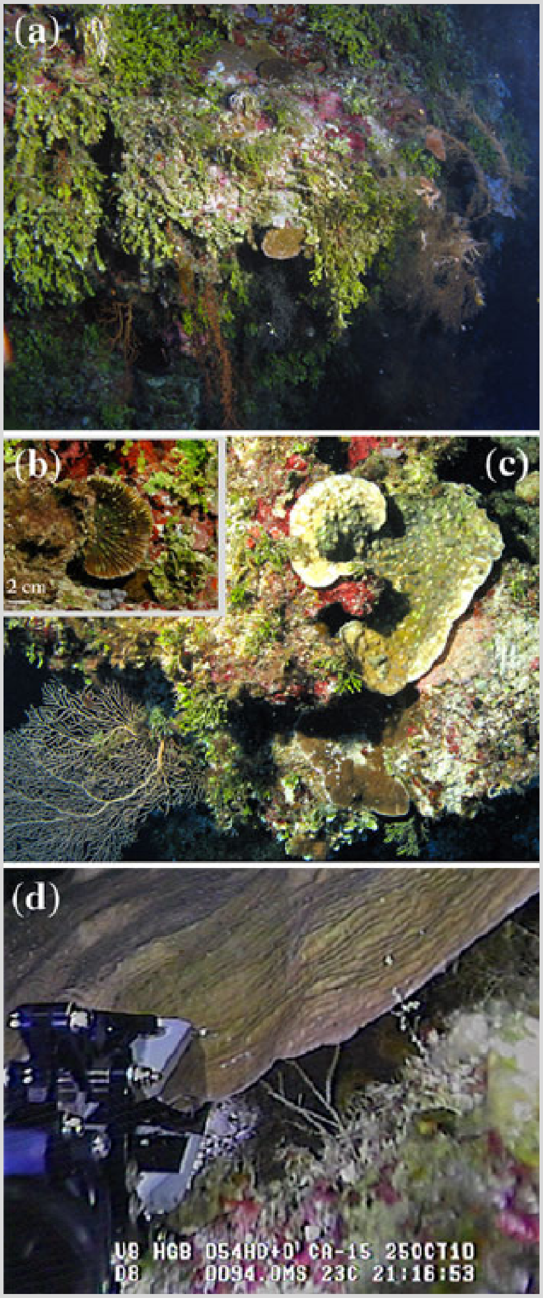

Fig. 1 **a** *Halimeda* curtains at 50 m, **b** *Echinomorpha nishihirai* at 40 m, **c** *Mycedium elephantotus* at 40 m, **d** ROV collecting from a large *Pachyseris speciosa* colony at 94 m

A research cruise was undertaken in October 2010 to explore potential mesophotic coral communities (30–150 m) in the recently established Coral Sea Conservation Zone (CSCZ). The CSCZ covers an area of almost one million square kilometres east of the Great Barrier Reef (Australia), with its reefs and atolls located hundreds of kilometres from the nearest landmass and surrounded by deep oceanic water. Three of the atolls in the CSCZ (West Holmes Reef [16.243°S, 147.874°E], East Holmes Reef [16.459°S, 148.024°E] and Flora Reef [16.755°S, 147.738°E]) were assessed using SCUBA and a Seabotix ROV. Shallow reef areas (<30 m) consisted largely of bare substrate with predominantly juvenile corals and very low coral cover due to past cyclone damage and thermal bleaching events. In contrast, the steep walls in 40–100 m depth were covered by extensive *Halimeda* curtains (Fig. 1a), which harboured diverse scleractinian coral communities, including *Acropora*, *Astreopora*, *Fungia*, *Galaxea*, *Goniastrea*, *Porites*, *Mycedium* (Fig. 1c), *Seriatopora* and *Turbinaria* spp., with *Pachyseris* (Fig. 1d), *Leptoseris* and *Montipora* spp. recorded to 102 m depth. At least one of the collected specimens represents a new species record for Australia: *Echinomorpha nishihirai* (Fig. 1b). Diverse communities of azooxanthellate octocorals were also observed to 150 m, the maximum depth of the ROV. These observations confirm the presence of mesophotic coral ecosystems (MCEs) along the walls of Coral Sea atolls and indicate that MCEs may form extensive features in the CSCZ. The deep-water coral communities may play an important role in the recovery of shallow reef areas on these isolated atolls by functioning as refugia from the repeated disturbances that have affected these reefs.

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