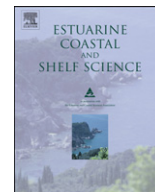


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## Coral bleaching at Little Cayman, Cayman Islands 2009

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## ABSTRACT

The global rise in sea temperature through anthropogenic climate change is affecting coral reef ecosystems through a phenomenon known as coral bleaching; that is, the whitening of corals due to the loss of the symbiotic zooxanthellae which impart corals with their characteristic vivid coloration. We describe aspects of the most prevalent episode of coral bleaching ever recorded at Little Cayman, Cayman Islands, during the fall of 2009. The most susceptible corals were found to be, in order, *Siderastrea siderea*, *Montastraea annularis*, and *Montastraea faveolata*, while *Diplora strigosa* and *Agaricia* spp. were less so, yet still showed considerable bleaching prevalence and severity. Those found to be least susceptible were *Porites porites*, *Porites astreoides*, and *Montastraea cavernosa*. These observations and other reported observations of coral bleaching, together with 29 years (1982–2010) of satellite-derived sea surface temperatures, were used to optimize bleaching predictions at this location. To do this a Degree Heating Weeks (DHW) and Peirce Skill Score (PSS) analysis was employed to calculate a local bleaching threshold above which bleaching was expected to occur. A threshold of 4.2 DHW had the highest skill, with a PSS of 0.70. The method outlined here could be applied to other regions to find the optimal bleaching threshold and improve bleaching predictions.

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## 1. Introduction

Temperature is one of the most important environmental variables limiting the distribution of reef-building corals (Dana, 1843; Vaughan, 1919), with most shallow-water tropical corals found within 18–30 °C (reviewed in Kleypas et al. (1999)). Sustained high temperature, however, causes large-scale coral bleaching, which is the whitening of the coral animal host due to the loss of symbiotic algae and/or a reduction in their photosynthetic pigments (reviewed by Glynn (1993), and Brown (1997)).

Little Cayman, Cayman Islands is a 17 km by 1.6 km low-lying island in the Western Caribbean Sea with a shallow (9–20 m) and narrow reef shelf that abruptly drops to great depths outside the euphotic zone. The island has a small human population (<200 full-time residents) and more than 50% of the nearshore waters are designated as a marine park or no-take zone, ensuring minimal direct anthropogenic stress.

The status of coral reefs in Little Cayman is well documented. The island has been included in the Atlantic and Gulf Rapid Reef Assessment (AGRRA, Manfrino et al., 2003), and the reefs have been monitored most years since 1998, with coral bleaching reported in Little Cayman previously in 1987, 1995, 1998, 2003, and 2005 (Ghiold and Smith, 1990; Coelho and Manfrino, 2007; Eakin et al., 2010). In 2002, 2004 and 2007 low levels (less than 5% of all colonies) of bleaching were reported. Prior to 2009, the most extensive bleaching occurred in 2005, but the prevalence (number of affected colonies divided by total number of coral colonies) of this event was surpassed in 2009 and remained high through the spring of 2010.

In July of 2009, parts of the Caribbean Sea began to experience a positive anomaly above the maximum summertime temperature, coincident with the development of an El Niño event (Bell et al., 2009).

Coral bleaching has been predicted using various tools, such as a simple fixed threshold based on climatology (Hoegh-Guldberg, 1999), degree heating weeks (DHW) (Gleeson and Strong, 1995; Goreau and Hayes, 1994), and time–temperature curves (Berkelmans, 2002). In this study we improve the DHW method by

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establishing a local threshold based on observational evidence; this can dramatically increase skill of the predictive method (van Hooidonk and Huber, 2009).

We describe the 2009 bleaching event and highlight the response of various coral species. Satellite-derived sea surface temperature (SST) data were used to quantify thermal anomalies expressed in DHWs at Little Cayman for the past 29 years (1982–2010). By combining the hind-cast with observations of bleaching, a refined, site-specific thermal threshold in DHWs was established.

## 2. Methods

### 2.1. Environmental data

The National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation Sea Surface Temperature version 2 (OISST) data were utilized for temperature analysis. This multi-source record combines ship and buoy data, together with satellite data from the Advanced Very High Resolution Radiometer (AVHRR) instrument (Reynolds et al., 2002). OISST data are recorded weekly at a 1° by 1° resolution. This product has been produced and archived since 1982 and is freely available at: <http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html>. A climatology has been constructed for this dataset based on the 1971–2000 SST analysis data utilizing the methodology outlined in Reynolds and Smith (1995) and Smith and Reynolds (1998). In situ sea temperature was recorded every 12 min with Hobo data loggers (Onset Corp.) deployed in Bloody Bay Marine Park from February 2008 to October 2009. Since July 2009 a Coral Reef Early Warning System (CREWS; Hendee et al., 2006) station has measured oceanographic and meteorological data on the north fringing reef near Bloody Bay Marine Park. These data were used to ground truth the OISST data in this study.

### 2.2. Bleaching observations and surveys

In October 2009 bleaching extent was quantified at two sites (Sailfin Reef and Grundy's Garden) using three randomly placed 10 m transects per site. Sailfin and Grundy's garden are spur and groove reefs at approximately 10 m depth. For each transect, all coral colonies that intersected with the transect line were identified to species. The centimeters of living coral cover directly under the line, not the area of the entire colony, was quantified and assessed for bleaching (complete visual absence of pigment) or paling (visually lighter shade of pigment than what was considered normal). These sites and an additional three locations (Nancy's Cup O'Tea, Rock Bottom and Snapshot) were resurveyed using four to six randomly placed transects per site in March, May, and June 2010 to monitor recovery from bleaching. The additional sites are also spur and groove reefs at ~10 m depth, except for the Rock Bottom location where the reef is at ~18 m depth. Because of time constraints, a line intersect method was chosen to survey the sites. The survey sites are located at previously established mooring buoys and no permanent markers were placed at the endings of the line transects. Therefore the location of the transect line was variable in each subsequent survey.

Bleaching prevalence was calculated as the number of affected (bleached or pale) colonies divided by the total number of colonies. Bleaching extent was calculated as the centimeters of bleached or pale tissue under the transect line divided by the total centimeters of all living tissue per colony recorded. Bleaching prevalence was therefore a population-level measure while bleaching extent represented the amount of area bleached per colony.

### 2.3. Degree heating weeks

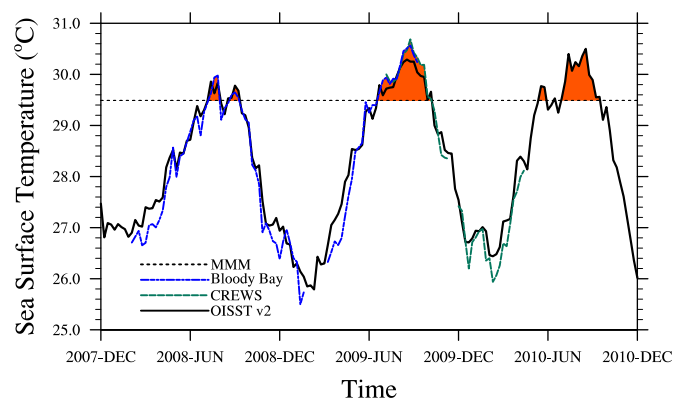
DHWs were calculated from OISST V2 data for the period 1982–2010. The DHW method is an accumulative stress index based on the sum of the positive anomalies above the maximum summertime temperature of the previous 12 weeks (Gleeson and Strong, 1995; Goreau and Hayes, 1994). The maximum monthly summertime temperature was defined as the warmest month in the 1971–2000 OISST climatology. The method used is similar to previous published work (Donner et al., 2007; van Hooidonk and Huber, 2009).

The skill of the DHW technique was assessed using the Peirce Skill Score (PSS, Peirce, 1884), a quantitative score often used in meteorology and other fields. This score has been applied successfully to predictions of bleaching in the past and allows for a quantitative improvement in bleaching prediction, or comparison between techniques (van Hooidonk and Huber, 2009). This score is defined as the hit rate minus the false alarm rate. Where the hit rate is the number of correct predictions of bleaching divided by the total number of bleaching events, and the false alarm rate is the number of incorrectly predicted bleaching events divided by the total number of non-bleaching events (Jolliffe and Stephenson, 2003). The score ranges from –1, indicating all predictions or hind-casts were wrong, to 1, representative of all predictions being correct. Constant or random predictions score 0. To calculate a skill score, a hind-cast of bleaching was made. This was done by comparing DHW data from 1982 to 2010 to bleaching episodes observed in those years. Bleaching reports were collected from the literature (Ghield and Smith, 1990; Coelho and Manfrino, 2007; Eakin et al., 2010) and reefbase.org. We classified a bleaching year as that in which bleaching prevalence was greater than 5% (1987, 1995, 1998, 2003, 2005, 2009). Years without any recorded observations were assumed to be non-bleaching years.

## 3. Results

### 3.1. Sea surface temperatures

In situ data from the CREWS station and the HOBO loggers in Bloody Bay Marine Park show very similar patterns to the OISST data (Fig. 1). When data from both in situ sources were averaged to



**Fig. 1.** Sea surface temperatures at Little Cayman from OISST v2 (black line), in situ data from the CREWS station (green), and temperature loggers in Bloody Bay Marine Park (blue). The horizontal dashed line indicates the maximum monthly mean (29.5 °C), the warmest temperature from the monthly climatology at Little Cayman. DHWs start to accumulate above this value (shaded red) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

weekly data and compared to the same periods of OISST data, the root mean squared errors (RSME) were 0.28 and 0.30 respectively, and both were highly correlated (Pearson's product–moment correlation,  $r = 0.99$ ,  $p < 0.005$ ).

### 3.2. Bleaching observations and surveys

In October 2009, 54 of the 69 observed coral colonies were affected (73% for the Sailfin location, 86% at Grundy's). Of those, 29 were pale and 25 were bleached. However, by March 2010, recovery was indicated by the two original sites having only 34% of the colonies bleached or pale (9 bleached colonies, 54 pale colonies, total for both sites  $N = 184$ ). Because no fixed end points for the intercept line were established, the method allowed for some variability in transects sampled between October 2009 and subsequent samplings. Therefore this recovery should not be seen as a recovery of individual colonies, but as a site-specific recovery. For all five sites combined in March 2010, 24% of all coral colonies were bleached or pale (18 bleached, 98 pale,  $N = 485$ ). Species-specific prevalence and severity for the 10 most common species in March 2010 combined for all sites are shown in Fig. 2. Over 91% of the colonies assessed were comprised of five reef-building coral genera: *Agaricia*, *Diploria*, *Montastraea*, *Porites* and *Siderastrea*. The species *Siderastrea siderea* and *Montastraea annularis* were most affected, whereas *Montastraea cavernosa*, *Porites porites*, and *Porites astreoides* were least affected (Fig. 2). By June 2010, most genera showed considerable recovery; however, a high proportion of colonies of *S. siderea* (66% and 75% at Sailfin and Grundy's respectively) remained pale, and average extent in pale or bleached tissue for this species remained high in June (43% and 38% at Sailfin and Grundy's).

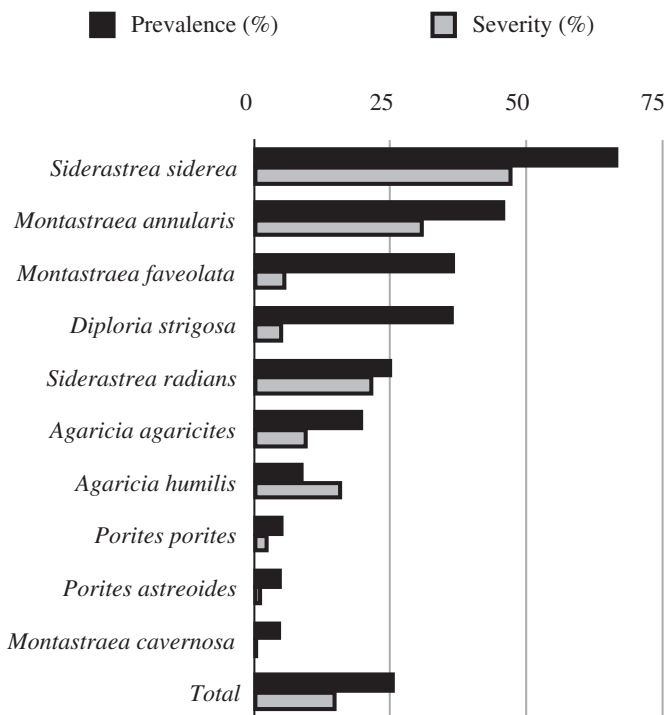


Fig. 2. Prevalence (black bars) and severity (gray bars) of bleaching and/or paling per species combined over all five locations in March 2010. The species are ordered by bleaching prevalence.

### 3.3. Degree heating weeks and predictive skill

The hind-casted thermal stress expressed in DHWs for the period 1982–2010 is shown in Fig. 3. The highest positive thermal anomaly was recorded in 1998, with 8.0 DHWs that year. All other reported bleaching years scored 4.2 DHWs or more, except 1987 when the hind-cast showed maximum thermal stress that year as 2 DHWs. Therefore the thermal threshold above which bleaching is predicted to occur on Little Cayman is set at 4.2 DHWs. With this threshold all but one bleaching event (1987) are correctly hind-casted, therefore the hit rate of this technique is 0.83. In the whole 1982–2010 period, the non-bleaching years when this threshold was exceeded were 2001, 2006 and 2010. In July 2006, 6% of the coral colonies observed were pale or patchy, but no corals

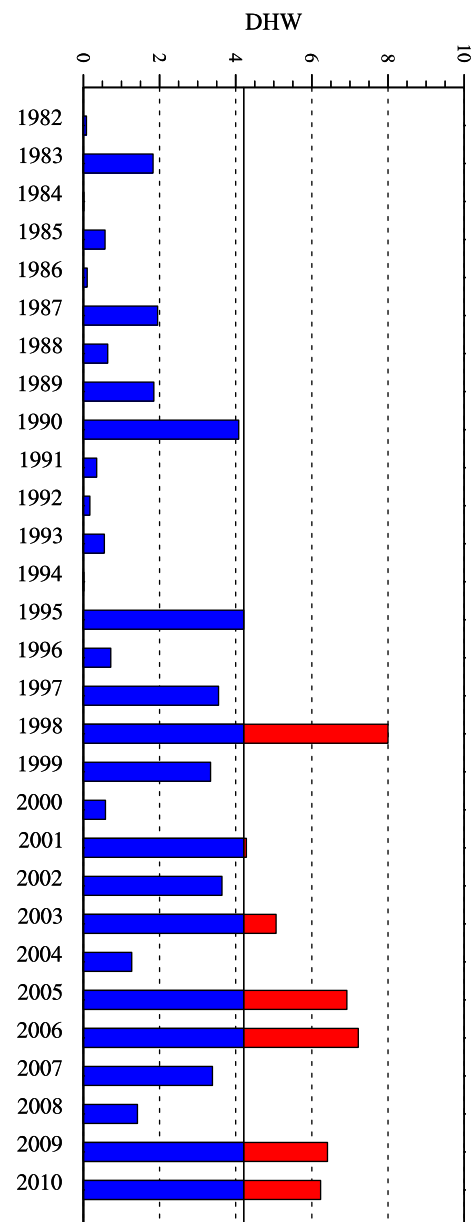


Fig. 3. Maximum Degree Heating Weeks (DHW) per year for the period 1982–2010 calculated from OISST v2 data at Little Cayman. The horizontal line represents the optimal bleaching threshold of 4.2 DHWs. DHWs above this threshold are red, indicating that bleaching is predicted, whereas below this threshold the bars are colored blue and no bleaching is projected (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

were bleached. In July 2007 again some corals were reported pale or patchy, only 0.2% of all colonies were reported bleached. Therefore 2006 and 2007 were not counted as bleaching years. Thus there are three false alarms, and 20 years when bleaching was correctly hind-casted to not occur. Therefore the false alarm rate is 0.13. The PSS is defined as the hit rate minus the false alarm rate (Jolliffe and Stephenson, 2003), resulting in a PSS of 0.70. This skill is comparable to other predictions of coral bleaching, the PSS of predictions based on observations of SST averaged over all reef locations globally was 0.83 (van Hooidonk and Huber, 2009, 2011).

#### 4. Discussion

Despite a large number of studies and monitoring of coral bleaching in the Caribbean Sea, there is still a lack of established species-specific bleaching susceptibilities, like those for the Indo-Pacific (e.g., Marshall and Baird, 2000; Loya et al., 2001). Species-specific susceptibilities have indeed been reported for more than two decades (e.g., Lasker et al., 1984; Jaap, 1985; Ghiold and Smith, 1990; CARICOMP, 1997; McField, 1999; Coelho and Manfrino, 2007), but some of these published reports have been contradictory. The time frames of many bleaching studies have varied widely, with some reporting bleaching sensitivities based on a single snapshot in time (Clark et al., 2009), and others following coral populations through the duration of a bleaching event (Brandt and McManus, 2009). Bleaching dynamics may indeed be similar among regions, but inconsistent observations may explain the contradictions.

It is well established that the hydrocoral *Millepora* and the non-calcareous zoanthid, *Palythoa caribaeorum*, are thermally sensitive and can be indicator species of thermal stress (e.g., Jaap, 1979), but beyond these two non-scleractinians there is no definitive listing of the relative susceptibilities for the common Caribbean corals to thermal stress. Ghiold and Smith (1990) reported prevalence for a bleaching event in the Cayman Islands in 1987. Of the species we report on, they describe the order of bleaching prevalence (from most prevalent to least) as: *Montastraea annularis*, *Diploria* spp., *Agaricia agaricites*, *Montastraea cavernosa*. This order is in exact agreement with our findings. In Coelho and Manfrino (2007) bleaching prevalence per genera for the 2003 bleaching event can be computed from their Table 3. They report bleaching prevalence was highest in the *Siderastrea* genus, followed by *Montastraea*, then *Agaricia*, next *Diploria* and finally the lowest prevalence was recorded for the *Porites* genus. Our findings are mostly in agreement with this order of prevalence, with an exception for *Montastraea cavernosa*. It should be noted that this species only represents a small fraction of all colonies observed in its genus; 121 total colonies of *Montastraea* spp. were observed, of those only 22 were *M. cavernosa*. Additionally, *Siderastrea radians* is considered a resilient and resistant species to a host of stressors (Lirman et al., 2002), yet it was moderately affected in prevalence and extent (Fig. 2). It is possible that the pale nature of *S. radians* introduced an observer error and that some colonies were marked as pale or bleached when in fact they might not have been affected at all.

Manzello et al. (2007) labeled Caribbean species either 'bleaching susceptible' or 'bleaching resistant'. This oversimplified the bleaching response (Fitt et al., 2001), but provided a first step in establishing the order of Caribbean coral bleaching susceptibility. As in that study, our results indicate that the *Montastraea annularis* spp. complex, *Siderastrea siderea*, and *Agaricia* spp., are particularly susceptible to bleaching. *S. siderea* showed a poor and delayed recovery in Little Cayman following the thermal stress event of 2009. The tolerance to thermal stress in *Porites astreoides* may help explain the recent increase of this species relative abundance on Caribbean reefs (Green et al., 2008).

Frequent monitoring before, during, and after the 2005 Caribbean mass bleaching event revealed that the more extensively bleached species and colonies were more susceptible to disease (Muller et al., 2008; Brandt and McManus, 2009) and that these diseases were the primary cause of mortality, not bleaching alone (Miller et al., 2006). Patterns of bleaching susceptibility may therefore also be linked in some way to species-specific disease risk.

In summary, *Porites astreoides* and *Montastraea cavernosa* may be the Caribbean's most resistant species to bleaching. The consistent bleaching sensitivity displayed by the *Montastraea annularis* spp. complex and *Siderastrea siderea* suggests they may be the Caribbean's most susceptible corals to thermal stress. However, further study is necessary to determine if the observed bleaching susceptibility corresponds to the risk of mortality, or if certain species are more apt to cope with bleaching. The decline of these primary reef builders may not result in a complete loss of living coral cover as smaller more proliferative species like *P. astreoides* replace it (Edmunds and Elahi, 2007; Green et al., 2008). However, the loss of three dimensional reef framework structures provided by such species will certainly result in reefs that look and likely function much differently than today. A future can now be modeled using the found differences between species and the thermal threshold found.

Using our method of calculating DHWs, the optimal threshold for bleaching in Little Cayman is 4.2 DHWs. This value should not be directly compared to thresholds calculated with different methods, as different source data can change the absolute values. The high PSS score (PSS = 0.70) indicates that a simple technique as accumulating thermal anomalies can explain bleaching responses in Little Cayman with great skill. The technique did produce three apparent false alarms, in 2001, 2006 and the other in 2010. In these years no bleaching was recorded in an AGGRA survey in July (pers. comm. Manfrino). In July 2006 6% of corals at all 5 locations were pale or patchy, indicating some stress. It is possible that a bleaching episode was not noticed in the surveys because the positive thermal anomaly occurred later than July that year. DHWs started to accumulate after July and exceeded the bleaching threshold of 4.2 DHWs from September until November. No other records of observations in 2006 have been found. The bleaching observed in March and May of 2010 was apparently a result from the positive thermal anomaly in 2009, and there are no records of observations later that year. Therefore, in the absence of records of bleaching, 2006 and 2010 are not counted as bleaching years.

The utility of the newly derived threshold lies in, a) being able to forecast on short time scales when bleaching is imminent, based on local conditions with a known skill, and, b) to incorporate this threshold in long term modeling efforts for Little Cayman. The short term forecasts could help direct monitoring efforts, or a marine park manager might direct additional in situ surveys when thermal anomalies indicates a chance of coral bleaching. Long term modeling can characterize the ecosystem response in Little Cayman under different climate scenarios. A possible improvement and sophistication in modeling local ecosystem responses to future climate changes could include both the different species susceptibilities and thresholds found. Finally, this study focused on Little Cayman, but the methods outlined are applicable to all locations with coral reefs, and when applied could lead to better predictions of coral bleaching.

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