ReefTemp: An interactive monitoring system for coral bleaching using high-resolution SST and improved stress predictors

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[1] Anomalously high sea surface temperatures (SST) have led to repeated mass coral bleaching events on a global scale. Existing satellite-based systems used to monitor conditions conducive to bleaching are based on low-resolution (0.5°, ~50 km) SST data. While these systems have served the research and management community well, they have inherent weaknesses that limit their capacity to predict stress on coral reefs at local scales, over which bleaching severity is known to vary dramatically. Here we discuss the development and testing of *ReefTemp*, a new operational remote sensing application for the Great Barrier Reef that assesses bleaching risk daily using: high-resolution (2 km) SST, regionally validated thermal stress indices, and color-graded legends directly related to past observations of bleaching severity. Given projections of sea temperature rise, *ReefTemp* is timely as it can accurately predict bleaching severity at a local scale and therefore help to give focus to future research and monitoring efforts.

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1. Introduction

[2] Large-scale coral bleaching events, caused by above average sea surface temperatures, have now affected nearly every major coral reef ecosystem on the planet [*Wilkinson*, 2002]. Coral bleaching is a stress response culminating in loss of symbiotic dinoflagellate algae from coral tissues. On the Great Barrier Reef (GBR), unusually warm sea temperatures have caused significant coral bleaching several times in the last decade, particularly in the summers of 1998, 2002 and 2006 [*Berkelmans et al.*, 2004; *Great Barrier Reef Marine Park Authority*, 2006]. Under most future climate projections, the frequency and severity of coral bleaching is expected to increase, leading to widespread concern about the future of the Great Barrier Reef in the face of global climate change [*Intergovernmental Panel on Climate Change*, 2007].

[3] Sea surface temperature anomalies and accumulated heat stress are currently monitored using global 0.5° resolution products, like 'Hotspots' and 'Degree Heating Weeks' [*Strong et al.*, 2006], available from the National Oceanic and Atmospheric Administration (NOAA). These products provide an effective early warning system for bleaching occurrence in reef regions around the world, but are not always accurate in predicting the severity of beaching at regional or local scales [*McClanahan et al.*, 2007]. There are three primary reasons for this lack of local accuracy: 1) temperature is highly variable on reefs at local scales [e.g., *Berkelmans et al.*, 2004, *Marshall and Baird*, 2000]; 2) the accumulated heat stress index commonly used, the degree heating week (accumulated time above a given temperature), does not incorporate the rate of temperature increase during a stress event – a factor that may be critical in the onset of the bleaching response; and 3) the use of fixed maximum thresholds that do not vary throughout the year – a factor that may result in missing bleaching stress early in the warm season. The first problem can be overcome by calculating thermal stress using high-resolution SST data set s (~1–2 km). An effective approach to address the second limitation is to calculate the rate at which heat stress accumulates – the 'heating rate' - in addition to the sum total heat stress. To overcome the third limitation, maximum thresholds should vary monthly to account for seasonal variations in bleaching responses [*Berkelmans and Willis*, 1999].

[4] Given the immediacy of the climate change issue and the pressing need for reef managers to have access to accurate and locally relevant monitoring programs [*Marshall and Schuttenberg*, 2006], it is timely to develop improved remote sensing applications for monitoring thermal anomalies that might cause coral bleaching. In this paper, we discuss *ReefTemp*, an application developed specifically to monitor conditions conducive to coral bleaching on the Great Barrier Reef and Coral Sea. *ReefTemp* builds on recent advances in remote sensing technology, incorporates heating rate to calculate bleaching risk, and includes an adaptable approach to color-grading bleach-

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ing risk that can evolve as a result of future change or be customised to other reef regions.

2. Methods

2.1. Climatology Calculation

[5] The climatology data set was derived from the analysis of NOAA environmental satellite Advanced Very High Resolution Radiometer (AVHRR) thermal data and includes composite data formed over intervals of 3 days of night and daytime passes over Australasia [*Griffin et al.*, 2004]. The representative SST for each grid cell (0.042 degrees of latitude, ~4 km, and 0.036 degrees of longitude, ~2 to 4.5 km) was determined by taking the SST value at the 65th percentile of the cumulative frequency distribution within each group of data to remove anomalous values caused by cloud and diurnal surface warming [*Griffin et al.*, 2004]. A mean monthly climatology was developed by calculating the average temperature for each month during the 11-year period of October 1993 to June 2003. The climatology datasets capture short-term variation and contain quality control measures for both the SST estimates and image shifting. The warming events of 1998 and 2002 have been included in the climatology since J. A. Maynard et al. (Major bleaching events increase thermal tolerance of corals, submitted to *Marine Biology*, 2008) found that thermal tolerance of corals can increase significantly following a warming event. Studies relating heat stress to bleaching response severity, therefore, need to be inclusive of warming events experienced recently.

2.2. Daily Data

[6] Daily data for *ReefTemp* comes from the Bureau of Meteorology Australia processing of the latest NOAA environmental satellite AVHRR thermal imagery to produce a 15-day composite SST data set (currently from NOAA AVHRR satellites 15, 17, and 18) at a resolution of 0.017995° (~2 km). The area of northeastern Australia in the resulting Australian Mercator Projection SST Mosaic is used in *ReefTemp* along with an age-of-data grid file. In cases where cloud cover obscures data collection, it is important to note that dense cloud cover is not conducive to further ocean warming [*Masiri et al.*, 2008]. For *ReefTemp*, 'cloud' pixels are replaced with the most recently calculated temperature value allowing for continuity in the estimation of bleaching risk and resulting in the tendency to slightly overestimate bleaching risk-precautionary approach to implementing research and monitoring programs.

2.3. Stress Indices

[7] Temperature stress is calculated by comparing daily data to the climatology data set (resampled to the 2 km grid using linear interpolation) for that month. The stress indices calculated are the 'degree heating days' (DHD) and the heating rate (HR), both of which describe the accumulation of heat stress during an event. Specifically, the DHD value is the summed positive deviations of daily average sea surface temperatures ($T_{Heating}$) from the climatology of long-term mean summer temperatures (*LMST*), for the summer period (December 1st to February 28th).

$$DHD = \sum \left(T_{Heating} - LMST \right) \qquad (1)$$

Degree heating days do not differentiate among a broad range of heat stresses. For example, three weeks at 1°C above the local long-term average results in the same number of DHDs as one week at 3°C [*Berkelmans et al.*, 2004]. Because a rapid increase in temperature does not allow time for the engagement of physiological mechanisms of acclimation the latter scenario is more stressful to corals. For this reason, *ReefTemp* also calculates the heating rate - the number of DHDs divided by the number of days in which temperatures ($T_{Heating}$) have exceeded the long-term mean summer temperatures (LMST). In mathematical terms, this is the average rate at which DHDs have accumulated throughout the summer (December 1st to February 28).

$$HR = DHD / \sum_{days} \left(T_{Heating} > LMST \right) \qquad (2)$$

2.4. Bleaching Observations

[8] To groundtruth the efficacy of *ReefTemp* in assessing bleaching risk, the relationship between model predictions and bleaching severity based on underwater video surveys by the Great Barrier Reef Marine Park Authority was analysed. Ten sites in the central GBR were surveyed in late February and early March 2002 (Figure 1), four weeks after observations of widespread bleaching were first reported. At each site, three random, replicated video belt transects (50 m^2) were recorded on the upper reef slope (2 to 4 m) and three were replicated on the lower reef slope (6 to 8 m). Bleaching in the video transects was quantified using standard methods [*English et al.*, 2004] at the 10 sites by estimating the proportion of all colonies within the five most common genera (*Acropora*, *Montipora*, *Favites*, *Pocillopora*, and *Porites*) affected by bleaching. These genera comprised a minimum of 72% (average of 86%) of the hard corals at these sites. Bleaching severity on transects was estimated as the average proportion of all colonies (within the listed genera) affected by bleaching on both the upper and lower reef slope at each site, including all visual signs of bleaching, i.e. fluorescing, partially bleached, or completely bleached.

2.5. Testing the Operational System

[9] The color gradations used to create risk assessments in *ReefTemp* are derived from regression analyses correlating the temperature stress indices to observed bleaching severity on the study reefs in 2002. To test the *ReefTemp* system during a bleaching event, data were processed for the 2005–2006 summer (December to February) for the southern GBR region when reefs in the Keppel Island area (23.15S, 150.9E) suffered 35–40% mortality of corals and compared to 2006–2007 summer data, when no reefs experienced significant bleaching.

3. Results and Discussion

[10] A unique feature of the *ReefTemp* application is its use of custom color gradations directly related to levels of stress known to cause bleaching on the shallow-water reefs (<12 meters) of the GBR and Coral Sea. Specifically, color-graded bleaching risk assessments from *ReefTemp* are based on the approximate strength of the index that corresponded

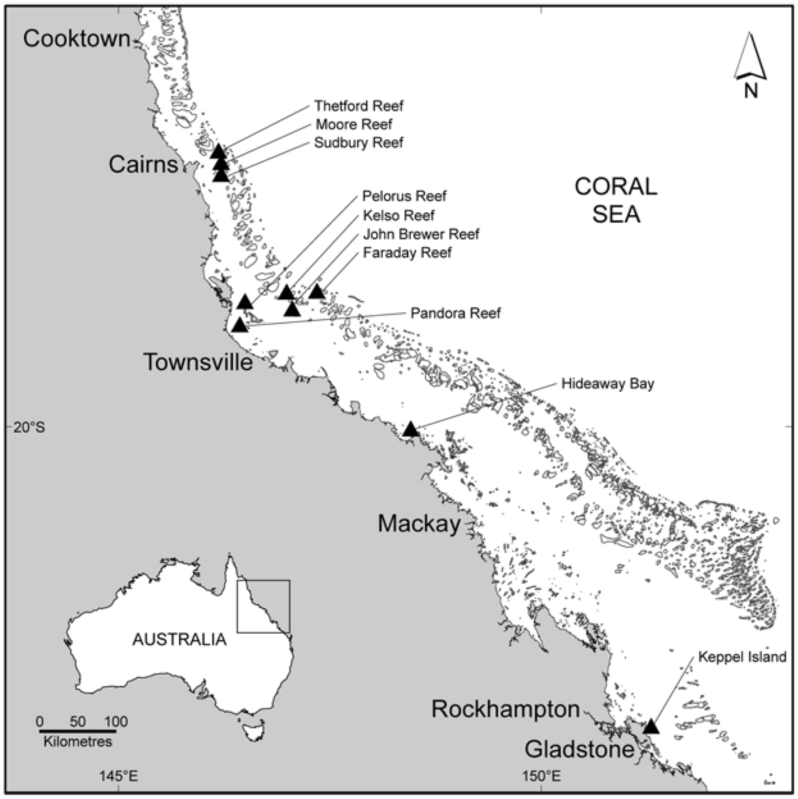

Figure 1. Map of ten sites on the Great Barrier Reef surveyed by the Great Barrier Reef Marine Park Authority in 2002 and used to calibrate the *ReefTemp* products.

to the minor (≤25% affected), moderate (26–50% affected), and severe (>50% affected) bleaching responses observed at the study sites in 2002 (Figure 2). For the degree heating days (DHDs) index, mild bleaching responses occurred at sites that incurred 60 or less DHDs. Moderate and severe bleaching categories approximated to 61–100 and >100 DHDs respectively. The heating rate index was a better predictor of bleaching severity (R^2 = 0.83) than the DHD index (R^2 = 0.69). Mild, moderate, and severe bleaching responses related to sites that experienced heating rates of <1.7, 1.7–2.4, and >2.4 respectively (see Figure 2).

[11] *ReefTemp* correctly predicted that bleaching responses in the southern GBR would be severe in 2006 (Table 1 and Figure 3). Both the degree heating days and heating rate indices predicted that bleaching responses would be severe (>50% colonies affected). In the southern GBR in 2006, rates of mortality in the Keppel Islands were as high as 40% but little to no bleaching occurred to the

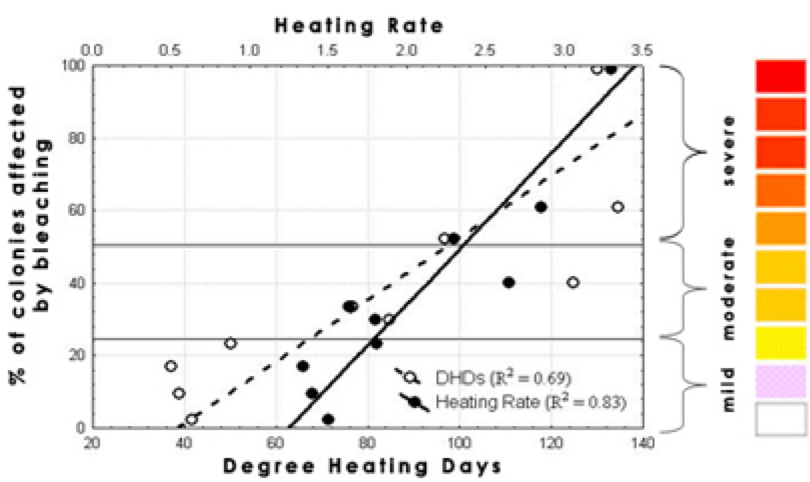

Figure 2. Color gradations used within *ReefTemp* are based on the approximate strength of each index that related to minor (≤25% affected), moderate (26 - 50% affected), and severe (>50% affected) bleaching responses at the sites in 2002.

Table 1. Bleaching Severity, Expressed as the Proportion of Colonies Affected by Bleaching, in 2006 and 2007 at Sites Within the Southern Great Barrier Reef[a]

		NOAA		*ReefTemp*			
	Bleaching Severity	DHW	Predicted	DHD	Predicted	Heating Rate	Predicted
			2006				
Great Keppel Island	77% (severe)	N/A	mild (X)	112	severe (√)	3.75	severe (√)
Heron Island	8% (mild)	4	mild (√)	70	mod (X)	0.5	mild (√)
Olympic Reef	5% (mild)	1	mild (√)	74	mod (X)	1	mild (√)
			2007				
Great Keppel Island	8% (mild)	N/A	none (X)	30	mild (√)	1	mild (√)
Heron Island	0% (none)	0	none (√)	12	mild (X)	0	none (√)
Olympic Reef	0% (none)	0	none (√)	24	mild (X)	0	none (√)

[a]The checks and crosses refer to a correct and incorrect prediction of bleaching response severity, respectively. DHD and DHW refer to degree heating days and weeks, respectively. Only the heating rate index, used in *ReefTemp*, accurately predicted the severity of bleaching responses at all three sites during both summers.

south at Heron Island and Wistari Reef, or to the north at Olympic Reef in the Swains. The heating rate index correctly predicted that bleaching responses at the end of the 2006 summer would be severe in the Keppels and mild elsewhere in the southern GBR and that little to no bleaching would occur in 2007 (see Table 1 and sites KI, HI, and OR, Figure 3). DHDs, however, incorrectly predicted that bleaching responses would be severe throughout the entire southern GBR in 2006 and mild to moderate at some locations in 2007. The disparity between the indices can be explained by the degree heating day (or week) approach not accounting for differences in the rate of heat stress accumulation, a weakness overcome by the heating rate index [*Maynard*, 2004].

[12] For the southern GBR in the summers of 2006 and 2007, the globally-oriented Degree Heating Week product from NOAA showed: 1) correctly that bleaching responses would be mild throughout the southern GBR east of Heron Island but, due to the size of the pixels in this product (0.5 × 0.5°) the severe temperature stress and bleaching at the Keppel Islands, which are only 15–20 km offshore, was missed because of their proximity to land, and 2) correctly that temperature stress was greater in 2006 than 2007 (Table 1). The contrasting risk assessments produced by

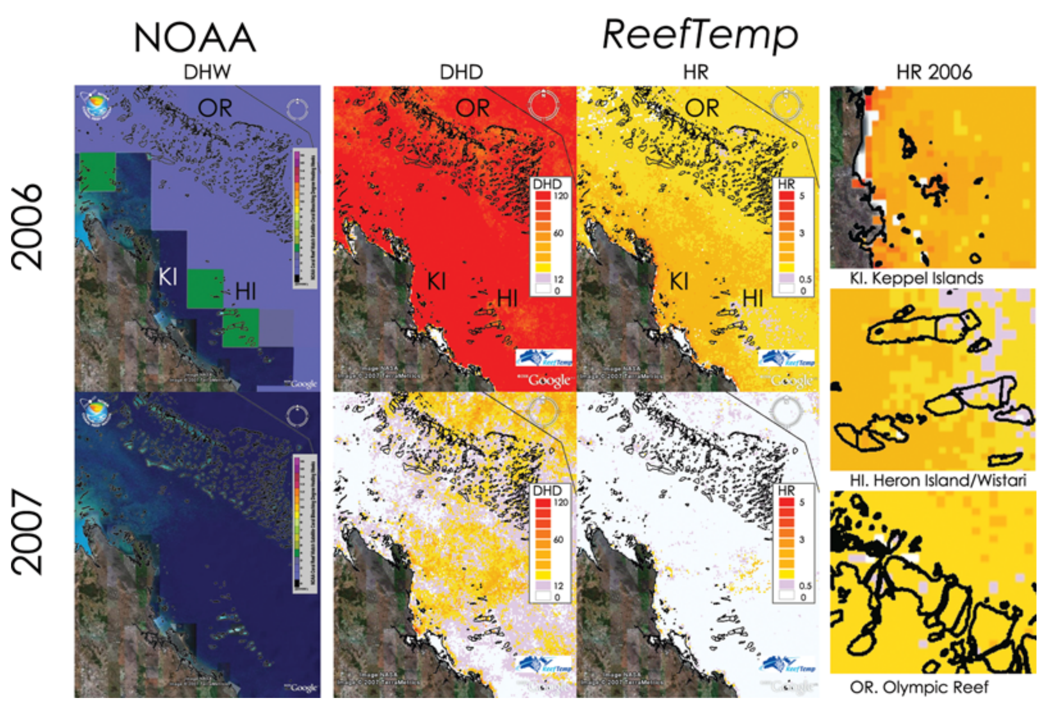

Figure 3. NOAA degree heating week (DHW), and *ReefTemp* images of degree heating days (DHD) and heating rate (HR) for the end of the summer, February 27, 2006 and 2007. The heating rate index used in *ReefTemp* performed the best accurately predicting that bleaching responses in the southern GBR in 2006 (HR 2006) would be severe at the Keppel Islands (KI) and extremely mild at Heron Island (HI) and Olympic Reef (OR). The site images highlight the usefulness of high-resolution SST data in the *ReefTemp* application as all of the temperature information shown at each site (under HR 2006) is summarized with the coloring of just one pixel in the NOAA DHW product.

these two products, and the inability of the NOAA DHW and HotSpot products to calculate temperature stress near shore, reflect the value of using high-resolution SST data and a regionally validated stress predictor. The inclusion of coastal pixels would, therefore, enhance the capabilities of the NOAA Coral Reef Watch products. This analysis also highlights the advantages for users of *ReefTemp* of displaying risk assessments in GoogleEarth™ – an interactive and customisable interface to view current and past images as well as search for, navigate to, and store frequently visited locations.

[13] The relationship between temperature and bleaching response severity is known to vary widely across reef regions [*Berkelmans et al.*, 2004], among species [*Baird and Marshall*, 2002], and to change over time (Maynard et al., submitted manuscript, 2007). Importantly though, as a result of future monitoring programs facilitated by *ReefTemp*, the color-graded legends could be changed to reflect: 1) changes to the thermal stress – bleaching relationship (due to acclimatization of coral populations and/or a change in the structure of coral communities) and/or improvements in our understanding of that relationship, 2) latitudinal variation in the thermal stress – bleaching relationship, at which point region-specific legends could be developed, 3) the relationship between temperature stress and the severity of bleaching responses elicited in corals at depths greater than 10 meters, and 4) other measures of bleaching response severity (e.g., the mortality due to bleaching rather than proportion of colonies affected by bleaching). Perhaps most importantly the color-graded legends could also be customized for use in areas outside the GBR and Coral Sea and calibrated prior to implementation or, alternatively, left as is and revised during a future bleaching event.

[14] In addition to the impacts of bleaching, the prevalence of coral diseases has been shown to increase significantly during summer, suggesting a link between seasonally high temperatures and disease incidence [*Willis et al.*, 2006]. *ReefTemp* can, therefore, also help to provide an improved understanding of small and large-scale spatial patterns in coral disease and coral disease outbreaks.

4. Conclusions

[15] Identifying strategies to mitigate climate change stressors and their interactions with multiple other variables (eg. poor water quality and overfishing) remain urgent challenges for the conservation and management of coral reefs worldwide. *ReefTemp* (available at: http://www.cmar.csiro.au/remotesensing/gbrmpa/ReefTemp.htm) and the heating rate stress index upon which it is based can help to meet these challenges by enabling more focused research and monitoring of bleaching events, the number and scale of which are predicted to escalate. As an example, the improved predictive power of *ReefTemp*, allows better planned, and more cost-effective field research to collect the empirical data needed to explore the capacity of corals to acclimatize to increasing thermal stress.

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