Limnol. Oceanogr., 53(4), 2008, 1369–1375

Improved predictions of coral bleaching using seasonal baselines and higher spatial resolution

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Abstract

Coral bleaching spread across the southern Great Barrier Reef in January 2006, after sea temperatures reached climatological summer maxima 2 months before normal. Current satellite-derived warning systems were unable to detect severe bleaching conditions in the region because of their use of a constant thermal threshold (summer maximum monthly mean) and low spatial resolution (50 km). Here it is shown that such problems can be ameliorated if the thermal threshold is adjusted for seasonal variation and a 4-km spatial resolution is used. We develop a seasonally and spatially improved thermal threshold for coral bleaching on the basis of a weekly climatology of sea surface temperatures extending from austral spring to late summer, and apply the method to two case-study sites. At both sites, and in particular at the nearshore site that was undetected by the 50-km satellite product, the seasonally adjusted thermal threshold produced a greatly improved consistency between accumulated heating and bleaching severity. The application of thermal stress algorithms that reflect the long-term mean pattern in seasonal variation allows coral bleaching to be forecast with higher precision.

Coral bleaching occurs when the mutualistic relationship between the coral host and symbiotic dinoflagellates is destabilized, and symbionts are lost from the coral tissues. This has occurred over vast areas of the world's oceans in response to periods of warmer-than-normal sea temperatures (Hoegh-Guldberg 1999). Under mild conditions, corals will recover their symbionts once the stress has been removed. If the warm conditions are severe and extended, however, corals may die (Anthony et al. 2007). Under projected global warming scenarios (Meehl et al. 2007), coral reef ecosystems are threatened on a worldwide scale (Hughes et al. 2003; Hoegh-Guldberg 2004).

All species of reef-building coral have temperature thresholds above which bleaching occurs. Thermal thresholds vary geographically, reflecting adaptation by corals and their symbionts to local water temperatures (over hundreds if not thousands of years). These thresholds underpin the highly successful coral bleaching prediction program at the National Oceanic and Atmospheric Administration (NOAA), which assumes a constant bleaching threshold 1°C above the long-term mean temperature of the warmest summer month, or "maximum monthly mean" (Strong et al. 2006). In most cases, exceeding this threshold for prolonged periods leads to mass coral bleaching and potential mortality.

Most organisms have the ability to acclimate to changes in temperature (Wilmer et al. 2000). In the case of reef-building corals, thermal thresholds have been shown to vary seasonally, decreasing in the winter by 1–2°C relative

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Acknowledgments

We acknowledge the National Aeronautics and Space Administration Ocean Biology Processing Group for provision of Moderate Resolution Imaging Spectroradiometer satellite data, particularly J. Wilding and B. Franz. We thank P. Marshall and J. Johnson of the Great Barrier Reef Marine Park Authority and J. C. Ortiz of the Coral Reef Targeted Research and Capacity Building Program for provision of coral bleaching survey data. We also thank P. Minnet, Rosenstiel School of Marine and Atmospheric Science, for advice on relative sensor calibrations. The Advanced Very High Resolution Radiometer Pathfinder sea surface temperature data were obtained from the Physical Oceanography Distributed Active Archive Center, http://podaac.jpl.nasa.gov.

This paper is a contribution of the "PIOS Adverse Eco-Feedbacks" project funded by the Pew Institute for Ocean Science, and the Australian Research Council Centre of Excellence for Coral Reef Studies.

to summer values (Berkelmans and Willis 1999). This seasonal variability in thermal threshold is not taken into account in algorithms underpinning the current NOAA coral bleaching prediction methodology (http://www.osdpd.noaa.gov/PSB/EPS/SST/methodology.html). The purpose of this study was to examine whether the absence of bleaching alert levels for the southern Great Barrier Reef (GBR) in January 2006 can be explained by the lack of seasonal adjustment in these algorithms.

As austral summer approached in late 2005, sea surface temperatures (SST) on the southern GBR (south of 20°S) rose rapidly, some locations already warming in December to levels normally not seen until February. Reefs across this region showed bleaching early in 2006, ranging from 10% to 90% (Great Barrier Reef Marine Park Authority [GBRMPA], www.gbrmpa.gov.au), with some inshore reef areas (Keppel Islands) experiencing near 100% bleaching in January 2006 and 36% mortality of corals by May 2006 (Berkelmans pers. comm.). However, the NOAA coral bleaching monitoring program (Strong et al. 2006) that uses a 50-km-resolution data set (excluding nearshore reefs such as Keppel Islands by a land mask) was not registering thermal anomalies signaling a major bleaching event, although conditions conducive to bleaching were indicated. Here, the SST anomalies and thermal stress in this event are explored using a seasonally adjusted thermal threshold and an improved spatial resolution and compared with those leading to the previous severe bleaching event of 2001–2002 in which coral bleaching was predicted successfully by the NOAA monitoring program.

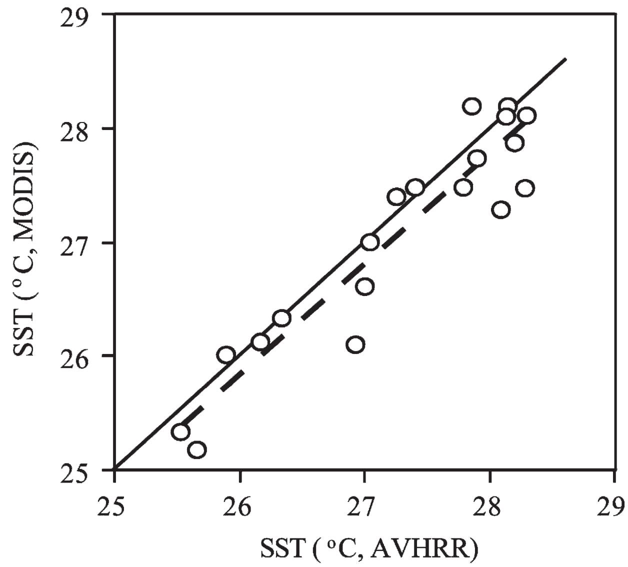

Fig. 1. Concordance of SST values derived from NASA MODIS and NOAA AVHRR products for Heron Island in 2005–2006. Solid line is the unity line ($x = y$) and the dashed line is the MODIS versus AVHRR regression, indicating that the 50-km AVHRR product records SST values that are on average 0.2°C higher than those recorded by the 4-km MODIS product over the temperature range.

Methods

Satellite SST data—SST data were derived from the moderate resolution imaging spectroradiometer (MODIS) aboard the National Aeronautics and Space Administration (NASA) Terra and Aqua satellites (modis.gsfc.nasa.gov) to produce an SST time series of high spatial resolution (1 km) for the period 2000–2006. The MODIS data were provided by the NASA ocean biology processing group (oceancolor.gsfc.nasa.gov) on a quasi-realtime basis throughout the 2005–2006 period. For the purpose of this comparative study, only MODIS Terra data are included since MODIS Aqua data are available from mid-2002 only, subsequent to the 2001–2002 coral bleaching event. Nighttime SST data only are used in this study, so as to avoid nonrepresentative data caused by intense daytime solar heating of the upper sea surface "skin" and to be more comparable with the NOAA satellite-derived SST products.

To produce a long reference period for generation of anomaly products consistent with that of NOAA bleaching predictions, the NOAA advanced very high resolution radiometer (AVHRR) pathfinder (PF) climatology (Kilpatrick et al. 2001; podaac.jpl.nasa.gov) was selected as the optimal baseline. This climatology represents the longest continuous time series of SST data (1985–2001) at relatively high spatial resolution (4 km), and hence, the strongest available representation of historical thermal conditions. It is worth noting that the statistical approach to estimation of the coefficients used in the atmospheric correction for the AVHRR SST produces a skin temperature biased by the mean skin-to-bulk temperature difference (Kilpatrick et al. 2001). The coefficients are derived by comparisons with bulk SST measurements from drifting and moored buoys so an average skin-to-bulk temperature difference is incorporated in the AVHRR SST retrieval (Minnet pers. comm.). The coefficients in the MODIS atmospheric correction algorithm are similarly derived by robust regression analysis of measured MODIS brightness temperatures and coincident in situ measurements, primarily buoy bulk SST measured at a depth of 1 m or more. The bulk temperatures are likewise converted to pseudoskin SST by incorporating an estimate of the mean skin-to-bulk SST difference (Minnet pers. comm.). Hence, using the AVHRR climatology as a baseline for generation of MODIS anomaly products is considered appropriate.

Two sets of SST files were generated from the MODIS data. Weekly (8-d) mean SST files were generated for the austral spring and summer months of November to March of 2005–2006 and 2001–2002 for the GBR region, extending from 11.0°S to 25.5°S and 142.5°E to 155.0°E. These data allowed high temporal resolution of seasonal variation in SST for these years. Monthly mean SST files were similarly generated for the annual periods of July 2005 to June 2006 and July 2001 to June 2002. As a basis for the seasonally adjusted threshold, the associated nighttime weekly and monthly SST climatology data were acquired from the AVHRR PF archive and used to generate weekly and monthly SST seasonal anomalies, respectively. Since the AVHRR PF climatology data are at a 4-km resolution, the 1-km resolution MODIS SST data were subsampled accordingly. To be consistent with the NOAA AVHRR

Table 1. Coral bleaching survey statistics for austral summers 2005–2006 and 2001–2002 acquired from the Great Barrier Reef Marine Park Authority and, for Heron Island, from the Coral Reef Targeted Research and Capacity Building Program. The data sources were derived from photographic transects undertaken during the bleaching events and enabled calculation of the percentage of coral colonies that were bleached. Survey statistics south of 21°S are in italics.

Survey site	Latitude (decimal degree)	Longitude (decimal degree)	Proportion of bleached corals in a community (%)
2005–2006			
Keppel–Halfway Is.	*−23.22*	*150.96*	*95*
Keppel–Middle Is.	*−23.16*	*150.92*	*81*
Keppel–North Is.	*−23.09*	*150.91*	*77*
Chinaman Reef	*−22.00*	*152.67*	*32*
Gannet Cay	*−21.98*	*152.48*	*27*
21-529 Reef	*−21.87*	*152.19*	*21*
Wreck Is.	*−23.32*	*151.98*	*16*
One Tree Is.	*−23.49*	*152.09*	*14*
Heron Is. (south)	*−23.46*	*151.93*	*12–20*
Heron Is. (north)	*−23.43*	*151.95*	*5–8*
Martin	−14.76	145.38	5
Low Islets	−16.39	145.57	5
Lizard Is.	−14.69	145.47	3
Rib	−18.47	146.88	1
Linnet	−14.79	145.35	1
Macgillivray	−14.65	145.49	1
North Direction	−14.75	145.52	1
Decapolis	−14.85	145.27	0
Carter	−14.53	145.59	0
Yonge	−14.57	145.62	0
No name	−14.63	145.65	0
Agincourt	−16.04	145.87	0
Mackay	−16.04	145.65	0
St. Crispin	−16.07	145.85	0
Opal	−16.21	145.91	0
Green Is.	−16.77	145.98	0
Fitzroy Is.	−16.92	146.00	0
Hastings	−16.50	146.03	0
Michaelmas	−16.55	146.05	0
John Brewer	−18.62	147.08	0
Hayman Is.	−20.06	148.90	0
Border Is.	−20.18	149.03	0
Langford	−20.08	148.88	0
19–131	−19.77	149.38	0
19–138	−19.81	149.43	0
20–104	−20.03	149.69	0
2001–2002			
Keppel − Miall Is.	*−23.15*	*150.90*	*99*
Keppel − Middle Is.	*−23.16*	*150.92*	*98*
Heron Is. (south)	*−23.46*	*151.93*	*1–25*
Heron Is. (north)	*−23.43*	*151.95*	*1–8*
Line Reef	−19.65	149.21	77
Bait Reef	−19.79	149.07	67
Hideaway Bay	−20.07	148.47	64
Border Is.	−20.17	149.04	58
Keswick Is.	−20.93	149.42	58
Thetford Reef	−16.80	146.20	53
Reef 19–123	−19.60	149.24	43
John Brewer	−18.61	147.06	39
Stone Is.	−20.05	148.33	38
Sudbury Reef	−16.95	146.16	37
Pandora Reef	−18.81	146.43	36
Florence Bay	−17.17	146.30	30
Outlier Reef	−19.54	149.34	27
Kelso Reef	−18.42	146.99	26
Faraday Reef	−18.41	147.35	25
Moore Reef	−16.85	146.23	12
Normandy	−17.25	146.08	8
Pelorus Is.	−18.56	146.50	8

maximum monthly mean (MMM) algorithm (Strong et al. 2006), accumulated thermal stress for the seasonally adjusted algorithm incorporated only SST values 1°C above the climatology. Analogously, on the basis of experimental data for summer versus winter bleaching susceptibilities (Berkelmans and Willis 1999), a lower heat-stress bound of MMM, 2°C, was used.

To compare with the key NOAA "HotSpots" and "Degree Heating Weeks" bleaching products, an MMM product was generated from the AVHRR PF data, representing the MMM SST attained per 4-km pixel throughout the climatology period (1985–2001). Using the MMM product as a common baseline, weekly and monthly MMM anomalies or bleaching HotSpots were generated for the same periods as for the SST seasonal anomalies described above. In both cases, only positive anomalies were considered. It is recognized that the climatology used for generation of the NOAA bleaching products is based on AVHRR observations from 1984 to 1993 only, shorter than the period represented by the AVHRR PF climatology (1985–2001). However, extending the NOAA climatology to a longer representative period has resulted in negligible differences at the coarser resolution (50 km × 50 km) used in the NOAA global products (Skirving pers. comm.). For example, the MMM value for Heron Island in the southern GBR derived from the 50-km NOAA AVHRR climatology is 27.3°C, whereas that derived from the 4-km AVHRR PF climatology is 27.4°C.

To compare the SST data derived from MODIS with that of the 50-km-resolution NOAA AVHRR product, weekly nighttime data for Heron Island for the period November 2005 to April 2006 were aligned for both products. Plotting the MODIS against AVHRR SST data demonstrated that the two products are generally highly consistent (indicated by close alignment along the unity line, Fig. 1). SST estimates for the 50-km AVHRR product were on average 0.2°C higher than those of MODIS over the 25–29°C temperature range. The difference between the observed correlation (r = 0.93) and that of a perfect relationship (r = 1) was likely to be attributable to differences in spatial resolution.

Coral bleaching data—Coral bleaching survey statistics for the austral summers of 2005–2006 and 2001–2002 were acquired from the GBRMPA. These data were complemented with bleaching survey statistics for Heron Island

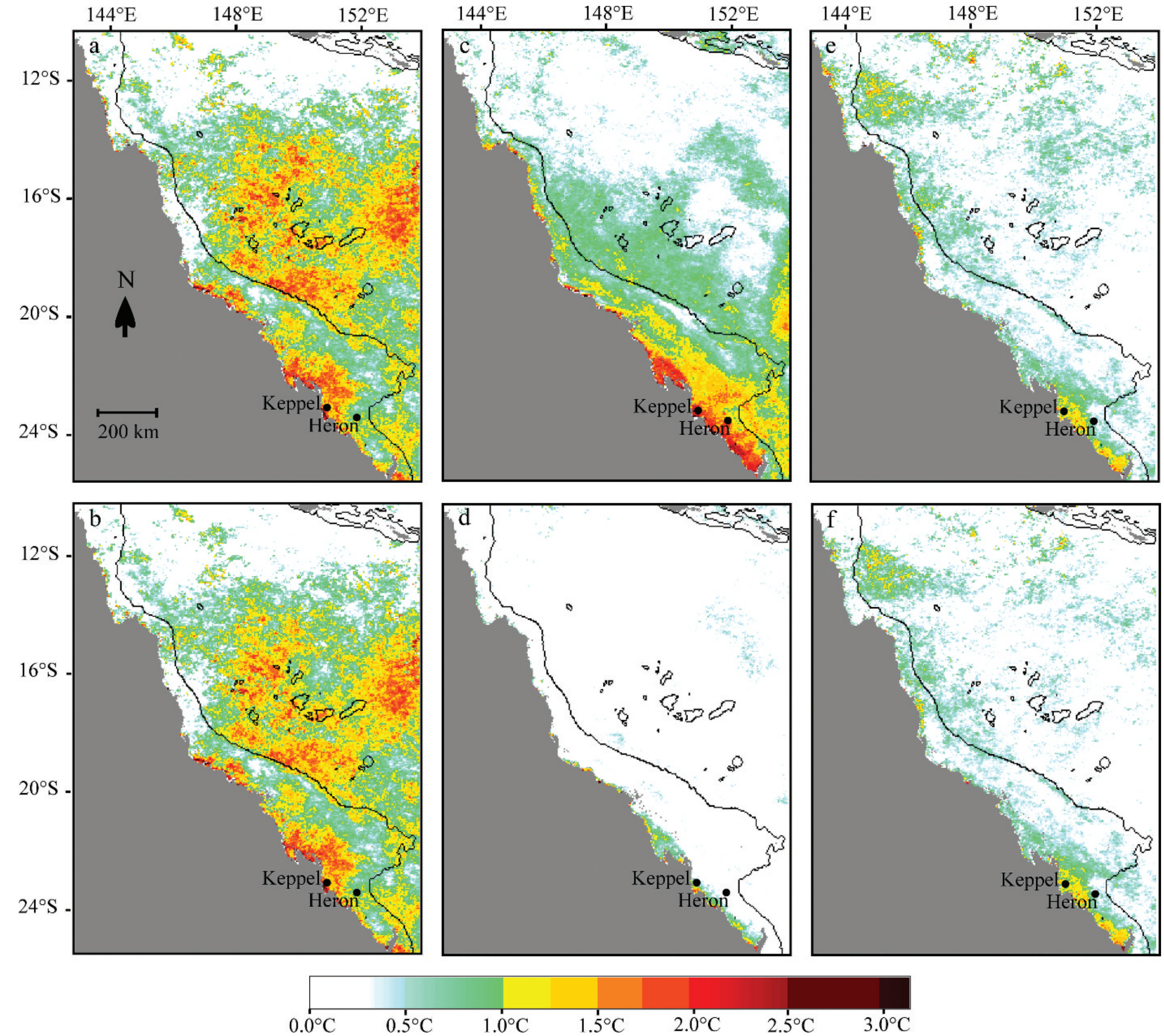

Fig. 2. SST monthly anomaly images for the Great Barrier Reef region (11.0–25.5°S, 142.5–154.0°E), computed (i) relative to the long-term seasonally adjusted climatology (SEAS) and (ii) relative to the maximum monthly mean (MMM). (a) SEAS anomaly for February 2002; (b) MMM anomaly for February 2002; (c) SEAS anomaly for December 2005; (d) MMM anomaly for December 2005; (e) SEAS anomaly for February 2006; and (f) MMM anomaly for February 2006. The 200-m isobath line is overlain.

sourced from the Coral Reef Targeted Research and Capacity Building (CRTR) Program (www.gefcoral.org). The data sources were derived from photographic transects undertaken during the bleaching events and enabled calculation of the percentage of coral colonies that were bleached. Detailed analysis of temperature time profiles was undertaken at selected locations for which coincident survey statistics were available for both the 2005–2006 and 2001–2002 events.

The GBRMPA coral bleaching survey statistics for 2005–2006 showed severe bleaching in the southern GBR, specifically south of 21°S (Table 1). Of the 34 sites surveyed along the length of the GBR (14.5–23.5°S), the remaining 26 sites showed 5% or less of coral communities bleached (Table 1). The GBRMPA survey sites for 2001–2002 were largely noncoincident with those of 2005–2006, and included only the Keppel Islands south of 21°S. These bleaching statistics contrasted markedly with the 2005–2006 event showing extensive bleaching (8–77%) primarily in the central GBR (15–20°S; Berkelmans et al. 2004), but with the most severe bleaching at the Keppel Islands (Table 1). The CRTR bleaching survey statistics for Heron Island showed a range of bleaching of 5–20% in 2005–2006, and comparably 1–25% in 2001–2002 (Table 1).

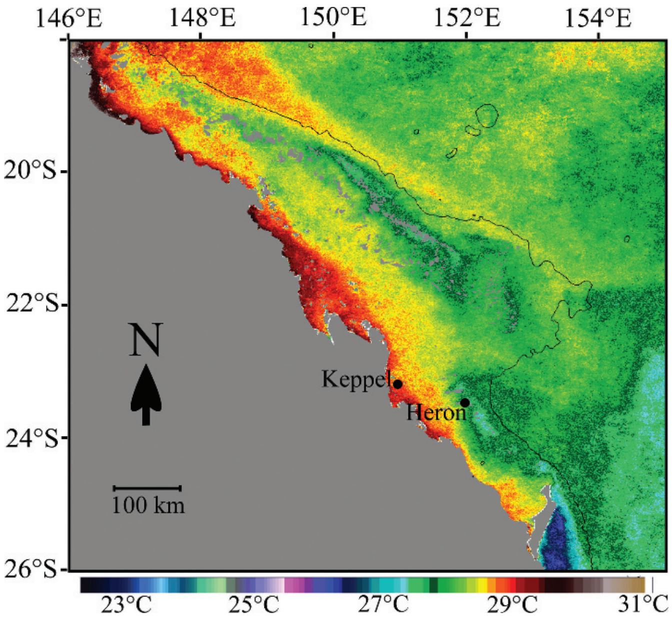

Fig. 3. Monthly mean SST for the southern Great Barrier Reef region (18.0–26.0°S, 146.0–155.0°E) for January 2006. The 200-m isobath line is overlain.

Results and discussion

SST anomalies derived using the seasonally adjusted (Fig. 2a) and the MMM (Fig. 2b) climatologies were strikingly similar during the 2001–2002 episode—demonstrating 85.3% agreement and a mean difference of 0.029°C for the remaining pixels. Most of the 2001–2002 warming occurred during February and was thus registered equally strongly by the two algorithms. In contrast, warming in 2005–2006 commenced very early in the season (November–December, Fig. 2c) and was thus only registered by the seasonal climatology. The rapid rise in SST in late 2005, in particular on the southern GBR, is clearly manifest in the December SST anomaly (Fig. 2c), maximum for 2005–2006 (Fig. 2e). According to the MMM anomaly criterion, there should have been little or no bleaching in this region in 2005–2006 (Fig. 2d,f).

Reefs near the Keppel Islands, which are located near the continental coast (Fig. 3), experienced near total bleaching in both events, with 98–99% of coral communities having bleached in 2001–2002 and 77–95% in 2005–2006 (Table 1). Heron Island, at a similar latitude but located offshore in the Capricorn–Bunker group of reefs (Fig. 3), experienced relatively minor coral bleaching in 2005–2006 (5–20%), comparable with that in 2001–2002 (1–25%, Table 1). The Capricorn–Bunker reefs, located on the shelf edge, are flushed by frequent intrusions of oceanic water (Steinberg 2007). The resultant mixing of relatively cooler deeper water (Skirving et al. 2006) is clearly evident even in the mean monthly signal (Fig. 3), leading to generally lower levels of bleaching relative to the shallow coastal Keppel Islands' location. Similarly, the northwestward direction of the intrusions would impinge the northeast aspect of Heron Island to a greater degree, the consequent upwelled, mixed waters resulting in comparatively lesser probability of bleaching here than on the more sheltered southwest aspect of the island, consistent with observations (Table 1).

Warming patterns at Keppel and Heron Islands in 2001–2002 were largely centered around the summer period, specifically mid-December to mid-February. Although the buildup of thermal stress occurred in two events, early and late warming were of almost equal proportions. Consequently, accumulated thermal stresses (as degree heating weeks) calculated on the basis of the seasonally adjusted as well as the MMM-based thresholds, were high at Keppel Islands and significant at Heron Island, and were partly reflected in observed levels of coral bleaching (Fig. 4a,b). In contrast, most of the warming during 2005–2006 occurred early in the season, in particular around the Keppel Islands (Fig. 4c). On the basis of the seasonally adjusted threshold, more than 75% of the accumulated heat stress for the 2005–2006 period occurred in November and December at this location, and exceeded the heat stress calculated for 2001–2002. Because of the low summer heating in January and February 2006 ($<$29°C), bleaching around Keppel Islands as predicted by the established MMM criterion was expected to be very low ($\sim$1 degree heating weeks). This discrepancy was equally pronounced for Heron Island in 2005–2006 (Fig. 4d). Here, all warming (although minor) calculated using the seasonal baseline occurred in December only, and led to bleaching of approximately 5–20% of the coral community. The maximum temperature reached on Heron Island reef during summer 2005–2006 was 28.2°C, below the NOAA MMM criterion of 28.3°C. Consequently, the MMM methodology produced no bleaching alerts for this location.

A previous study (Berkelmans and Willis 1999) has demonstrated that winter bleaching thresholds for corals are 1–2°C lower than summer thresholds. This change in threshold is probably related to the physiological expression of molecular elements that enhance the ability of the symbiosis to tolerate the higher temperatures as summer approaches (Gates and Edmunds 1999). Thus, in years where warming occurs early in the season, thermal stress estimators that take account of such seasonal variation are likely to produce more well-founded predictions of coral bleaching than those based on a constant value such as the MMM baseline. According to the MMM anomaly criterion, there should have been nonsignificant bleaching at the Keppel Islands and no bleaching at all on Heron Island in 2005–2006.

Since additional variables such as solar irradiance (Fitt et al. 2001) and varying susceptibility of differing coral community types (McClanahan et al. 2007) also contribute to the coral stress response, thermal anomalies only partially account for observed bleaching patterns. Nonetheless, this study has demonstrated that predictions of coral bleaching from space-based sensors are vastly improved if seasonal thermal variation of corals is accounted for in the algorithms. The development of remote thermal sensing models that incorporate information about seasonal biological processes and varying sensitivities to environmental variables is likely to produce more accurate tools for predicting stress in coral communities under a rapidly changing global climate.

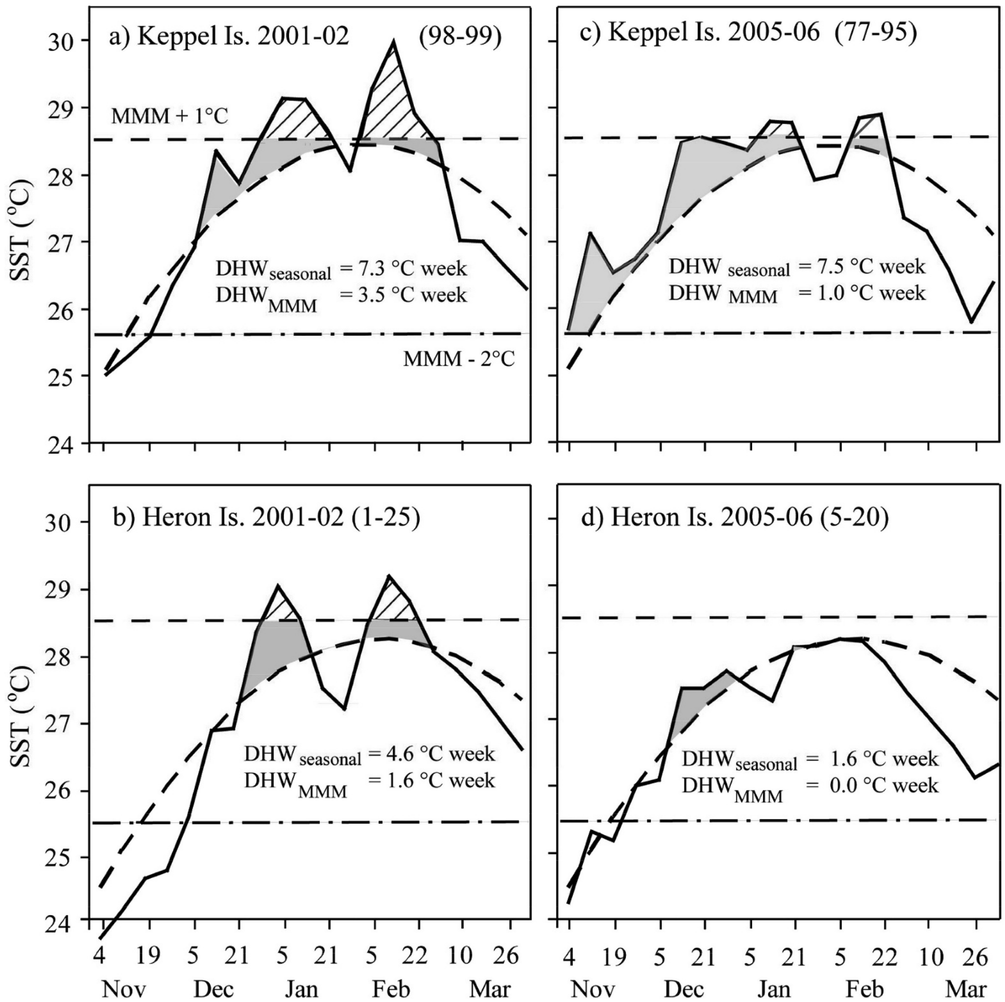

Fig. 4. Weekly SST anomalies for Keppel and Heron Islands during November–March for 2001–2002 and 2005–2006. The maximum monthly mean (MMM) value + 1°C is indicated by the upper dashed horizontal line. The dashed dotted line is the MMM value − 2°C and is used as a cutoff line below which heating stress is assumed to be unlikely. The dashed curve represents the weekly seasonal climatology + 1°C. Hatched areas indicate accumulated thermal stress as calculated by the MMM methodology, and gray + hatched areas represent accumulated heat stress on the basis of the seasonally adjusted algorithm. Observed levels (range averages) of coral bleaching are shown in brackets: (a) Keppel 2001–2002 (98–99%), (b) Heron 2001–2002 (1–25%), (c) Keppel 2005–2006 (77–95%), and (d) Heron 2005–2006 (5–20%).

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Received: 10 August 2007
Accepted: 25 January 2008
Amended: 19 February 2008