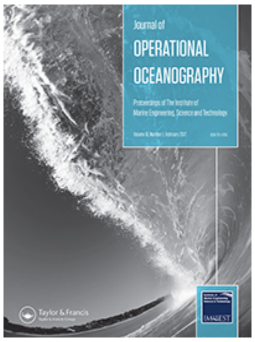

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Temperature and light patterns at four reefs along the Great Barrier Reef during the 2015–2016 austral summer: understanding patterns of observed coral bleaching

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Temperature and light patterns at four reefs along the Great Barrier Reef during the 2015–2016 austral summer: understanding patterns of observed coral bleaching

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ABSTRACT

Data from real-time sensor networks along the Great Barrier Reef (GBR) over the 2015–2016 austral summer showed that reef water temperatures exceeded empirical coral bleaching thresholds at a number of sites. Temperatures in the southern GBR were within historically normal limits with temperatures below the empirical bleaching threshold. The central GBR just reached the empirical bleaching threshold while, in the north, Lizard Island recorded four consecutive days above the bleaching threshold. Thursday Island in the far northern GBR experienced 10 days above the bleaching threshold. The in situ data predicted only slight bleaching in the southern GBR, moderate bleaching in the central GBR, widespread bleaching in the north and severe bleaching in the far north, which compares well with the initial survey data. Peak temperatures occurred later in the year in the north (mid-March 2016) than in the south (early February 2015) with temperatures remaining above the long-term mean well into the austral autumn. Comparison against satellite sea surface temperature data highlighted issues of cloud cover with data only being available for 30–40% of days over the summer. While the agreement with the in situ data was good, the satellite data missed fine-scale events and under-estimated the event at Thursday Island.

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Coral bleaching; Great Barrier Reef; El Niño; thermal patterns; sensor networks; SST validation

Introduction

For Southern Hemisphere coral reefs the 2015–2016 austral summer was predicted to include higher than normal sea surface temperatures (SST) with an associated increased risk of coral bleaching following similar El Niño-related conditions in the Northern Hemisphere boreal summer in mid-2015 (Normile 2016). Australia's Great Barrier Reef (GBR), for example, typically experiences above-average ocean temperatures in the late summer of the second year of an El Niño event (Lough 2007). A series of bleaching alerts, based on satellite SST data, were issued for the GBR for the 2015–2016 summer period (NOAA 2016).

This paper presents temperature, light and atmospheric data collected from real-time ocean monitoring stations located along the GBR to document the in situ reef conditions over the 2015–2016 austral summer period, contextualised using historical data, to gain an insight into the environmental factors impacting the 2015–2016 bleaching event. The real-time in situ data form an important source to understand and respond to thermal events as they unfold and, through the on-site metrological data, to understand the processes that act to cause heat accumulation and dissipation. The data provide an important context in understanding biological responses to warm water events both as bleaching and as subsequent coral mortality or recovery. Finally the in situ data provide a validation source for remotely sensed data and importantly provide data at times when cloud cover can limit the effectiveness of satellite-based measurements.

Materials

Sites and sensors

A series of real-time coral reef observing stations have been established along the GBR in north-eastern Australia (AIMS 2016b) with the earliest stations established in the early 1990s and a series of newer stations established between 2008 and 2010 at the GBR island research stations under the Australian Integrated Marine Observing System (IMOS). At each station, temperature sensors (SeaBird™ SBE37 and SBE39 instruments) were deployed at varying depths around reefs in a sensor network configuration (a central control and

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communications node or buoy and smaller remote nodes located around the reef that communicate back to the central node (Bainbridge et al. 2010)). An automated weather station (Vaisala™ WXT520 instrument) provided above-water measurements of wind speed and direction, humidity, air temperature and barometric pressure. Light, as Photosynthetically Active Radiation (PAR), was measured with an above-water co-located LI-COR™ LI-192 quantum sensor. All data were run through automated Quality Control (QC) routines (range and rate of change checking) and then manually checked (visual de-trending, removal of anomalous points). A web site was established to present the real-time daily average temperatures with a series of bleaching risk indicators based on the historical data.

Four stations or sites were chosen to give a spread of geographic locations, running from the southern GBR to the Torres Strait in the north, in order to capture regional differences and to reflect sites where pre- and post-bleaching field surveys were planned. Where possible mid- to outer-shelf lagoonal reefs were chosen where good data were available from a temperature sensor located 2–4 m in depth. The sites were: Heron Island – an outer-shelf lagoonal reef in the Capricorn Bunker group of reefs in the southern GBR; Davies Reef – a mid-shelf lagoonal reef in the central GBR; Lizard Island – a high continental mid-shelf island in the northern GBR with a surrounding fringing reef and extensive lagoonal system, and Thursday Island, a fringing reef around a high island in the southern part of the Torres Straits or far-northern GBR (Table 1, Figure 1).

The source data were 10-minute readings with the temperature data averaged to give daily average values while the light data were subsetted to only include data from 8 am to 4 pm (day time); the subsetted light data were then averaged to give average day-time daily light values. The daily light values were smoothed using a seven-day moving window. The light sensor at Davies Reef malfunctioned and so the equivalent sensor at Myrmidon Reef, 60 km NNW from Davies, was used instead. The light sensor at Thursday Island also failed during the study period and so data from an equivalent station (same sensors and installation) at Masig (Yorke) Island, some 100 km north-east, were used instead. While the failure of these sensors is not ideal, this paper will only look at regional light fields and so there is less dependency on having the above-water light sensors co-located with the in-water sensors.

Table 1. Sites and sensor locations and details (sites ordered south to north).

Site	Latitude (°N)	Shelf position	Sensor location	Sensor depth (m)	Climatology period
Heron Island	−23	Outer	Lagoon	2	August 2008–May 2015
Davies Reef	−18	Mid-Shelf	Lagoon	4	May 1998–September 2015
Lizard Island	−14	Mid-shelf	Lagoon	4	August 2010–July 2015
Thursday Island	−10	Inshore	Reef Slope	4	May 1998–September 2015

Note that it is planned to make the temperature data for the 2015–2016 bleaching event from the various participating programmes, including loggers, moorings and sensor networks, available as a single data product.

Climatologies

At each site the quality-controlled 10-minute observations were averaged based on the ordinal day of the year; for example all of the historical quality-controlled data for the 1st of January were averaged to give a mean water temperature and standard deviation for that day for the climatology period. Leap years were accounted for by explicitly including the 29th of February, although with fewer data points. The daily average water temperatures and associated variability were then smoothed by running a high order polynomial over the data to remove spikes to give the final climatology as daily average temperature values for that sensor for the climatology period, along with daily measures of the historical temperature variability. The resulting climatology was constructed by plotting the mean value and then overlaying plots of the mean values plus and minus the daily standard deviation (SD) value to show envelopes for the mean ±1, ±2 and ±3 SD values. Standard deviations varied with site and time of year but were typically in the range of 0.5–0.8°C.

The climatology not only contextualises current conditions against the historical values but the variability defines temperatures that are within the 'normal' range against those which are extreme. For this work, temperatures within the ±2 SD limits were considered to be 'normal' in that statistically they account for 95% of the data, temperatures between the 2 and 3 SD bounds were considered to be 'unusual' and those outside the ±3 SD limits as being 'extreme' (representing less than 1% of the data). Thus the SD bounds identified water temperatures that represent unusual or extreme events (Bainbridge & Berkelmans 2014).

Bleaching thresholds

Using in situ water temperature data from bleaching and non-bleaching years, an empirical threshold for observed bleaching can be determined. Empirical thresholds have been developed for reefs along the GBR (Berkelmans 2002) using previous widespread bleaching and near-

Figure 1. Map showing the location of the observing sites.

bleaching events (in particular the 1998 bleaching event). The thresholds are expressed as an exposure curve – that is, as temperature versus exposure (time in days). For this study the bleaching threshold was defined as the temperature where one day of exposure is empirically linked to observed bleaching (Berkelmans 2002).

Degree Heating Weeks

Degree Heating Weeks (DHW) is a measure of heat accumulation calculated by looking at the difference between the daily observed water temperature and the climatology value, averaged over a sliding window of 84 days (12 weeks) divided by seven to give a weekly value (Liu et al. 2006; Mumby et al. 2004). This effectively measures the area between the daily temperature plot and the climatology and gives a measure of the accumulated thermal 'load' or 'capacitance' in the system. A value of zero means that the thermal load is normal for that time of year; positive values indicate an above normal accumulation of heat stress or load; negative values indicate heat dissipation or cooling. Increases in DHW values do not necessarily indicate that the water is getting warmer but that there is an increasing difference between the measured and historical temperature values.

The DHW measure used differed to that used by the NOAA Coral Reef Watch programme (Liu et al. 2006) in that it included negative values representing cooling events and, as it was based on accurate in-water measurements, it included small differences between the measured daily values and the climatology; some satellite-based methods only use values where the difference is greater than 1°C (Liu et al. 2006; Maynard et al. 2008). For remote sensing, 4°C-weeks is seen as a warning level of thermal accumulation while 8°C-weeks indicates extreme warming (Liu et al. 2006). For this study these levels were used to indicate medium (4°C-weeks) and high (8°C-weeks) thermal loads.

Results

While most sites have multi-year data available, this paper will focus on the 2015–2016 austral summer using data from the 1st of September 2015 through to the 1st of June 2016. For this period the main temperature indicators for each site are shown in Table 2.

The reefs to the north had a greater number of days above the empirical bleaching thresholds and a greater number of days above the two and three SD limits (Table 2). Maximum temperatures were also recorded later in the northern reefs (mid-March 2016) than in the southern reefs (early February 2016). Thursday Island, in the Torres Strait, had 10 days above the empirical bleaching threshold and a month over the +2 SD limits. On the 13th of March 2016 the station recorded a daily average water temperature of 31.9°C, which is a new record, the previous high being 31.6°C on the 21st of February 2010.

Table 2. Days above the various bleaching thresholds from the period 1st September 2015 to the 1st of June 2016, the maximum summer temp is a daily average temperature (sites ordered south to north).

Site	Max. summer temp (°C)	Warmest day	No. of days above bleaching threshold	No. of days above +2 SD limits	No. of days above +3 SD limits
Heron Island	28.3	4 February 2016	0	7	0
Davies Reef	29.8	1 March 2016	1	31	0
Lizard Island	30.7	3 March 2016	4	9	1
Thursday Island	31.9	13 March 2016	10	31	11

Heron Island

The daily average water temperature at Heron Island did not approach the empirical bleaching threshold (Figure 2(a)) with temperatures mostly within the ±2 SD boundaries and so considered to be normal. The DHW plot (Figure 3(a)) showed that the thermal load remained neutral until March 2016 and only started to increase above the climatology late in the summer from April through to June 2016 when temperatures were elevated relative to the climatology but still well below the empirical bleaching threshold. Note that the thermal stress continued beyond early June 2016 and so the thermal stress event continued well into the austral winter.

Davies Reef

Davies Reef experienced one day above the empirical bleaching threshold and 31 days above the +2 SD climatology limits (Figure 2(b)), although these mostly occurred later in the year past the time of peak temperatures. As a result, corals would have been exposed to water temperatures at or just exceeding the empirical bleaching threshold. The heat load, based on the DHW (Figure 3 (b)), was only moderate during the time of highest temperatures (late February/early March 2016) but the system continued to gain heat well into June 2016. The DHW plot shows that the thermal load was above 8°C-weeks, which represents a high thermal load, for two months. For the three months, from March to May 2016 inclusive, water temperatures remained on average 1°C above the climatology or long-term mean. As with Heron Island the relative heat load continued to rise well past late summer and into winter.

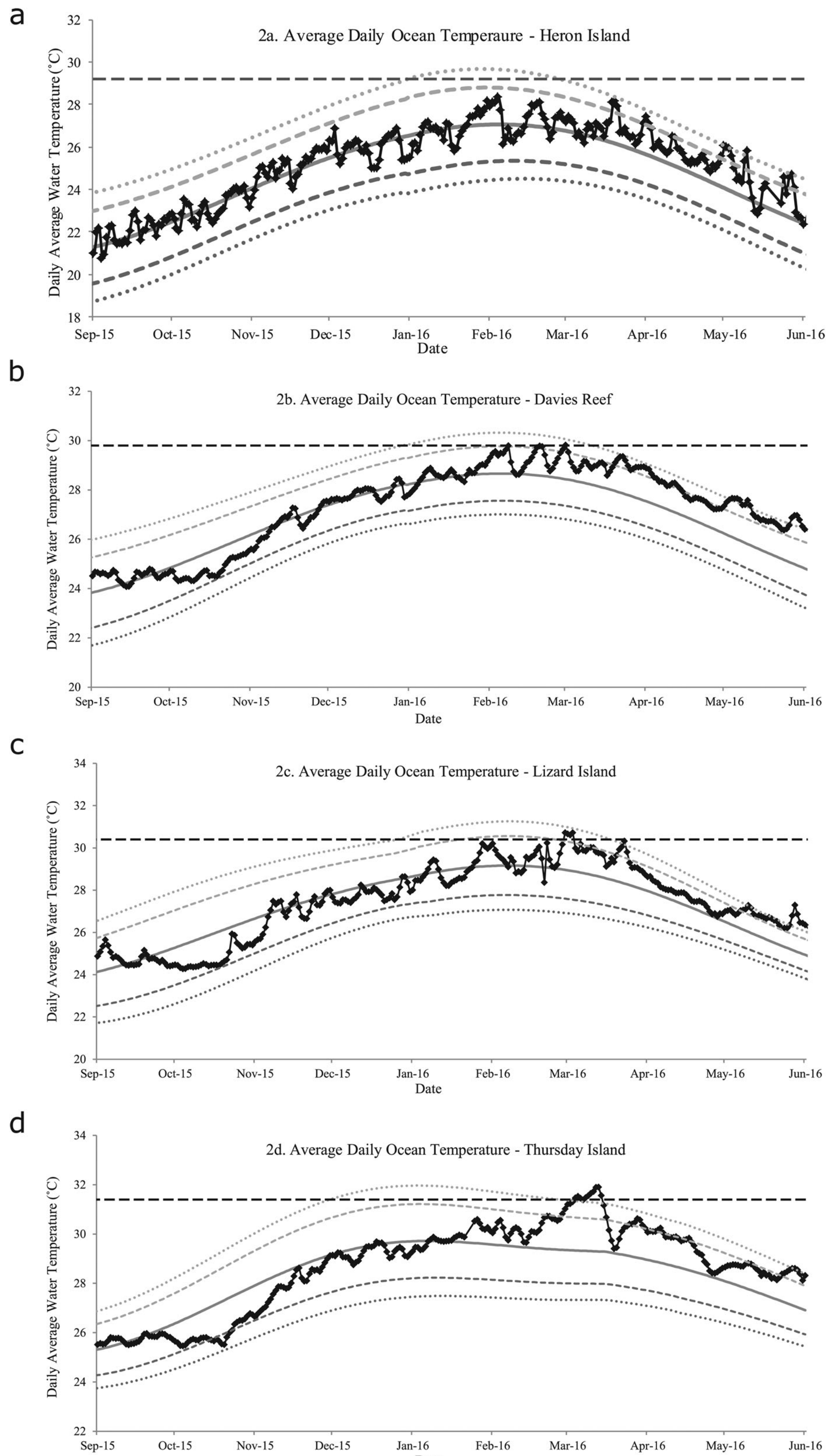

Figure 2. Temperature plot for each site for the 2015–2016 austral summer. Solid grey line is the climatology value, long dashed grey lines are the ±2 SD limits, short dashed grey lines are the ±3 SD limits, dashed black line is the bleaching threshold while the solid black line with diamond markers is the daily average measured water temperature. Date marks represent the start of the month.

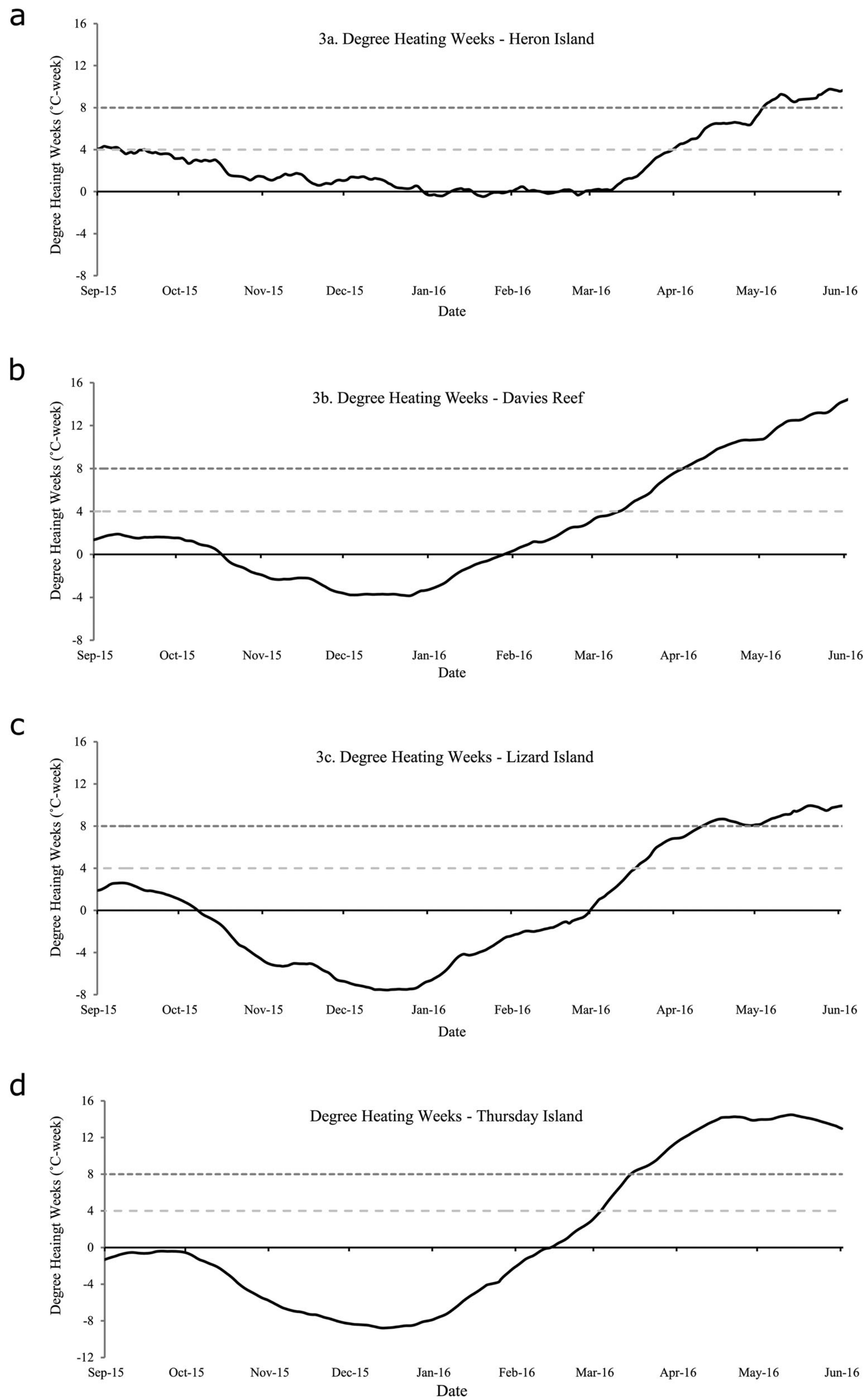

Figure 3. DHW values for each site for the 2015–2016 austral summer, the dashed light grey line represents the medium thermal load limit (4°C-weeks) and the dashed dark grey line the high thermal load limit (8°C-weeks). Date marks represent the start of the month.

Lizard Island

The island lagoon experienced four days above the empirical bleaching threshold and nine days above the +2 SD climatology limits and one day above the +3 SD limits (Figure 2(c)). Temperatures peaked in early February, temporarily declined only to peak again at higher levels in early March 2016. The DHW plot (Figure 3(c)) shows a rise in the thermal load from neutral conditions in March to above 8°C-weeks by mid-April 2016, which, unlike the reefs to the south, is closer to the time of seasonal maximum temperatures. The co-occurrence of peak temperatures with high heat loads means that reefs are not only experiencing temperatures at or above the empirical bleaching thresholds but that the system maintains a high heat load for a number of subsequent months.

Thursday Island

Thursday Island experienced the most extreme thermal conditions of the reefs observed with a total of 10 days above the empirical bleaching threshold and temperatures 2.6°C above normal (in mid-March 2016). From the 8th of March 2016 there were three consecutive days above the bleaching threshold, followed by one day at the threshold and then another seven days above the threshold (Figure 2(d)). The DHW at Thursday Island (Figure 3(d)) was similar to Lizard Island with a substantial heat load in the system at the time of seasonally highest temperatures (mid-March 2016) with this heat load being maintained well into June 2016 with a DHW value of over 14°C-weeks in mid-April 2016.

Light

Daily (8 am–4 pm) average light levels showed considerable variability over the 2015–2016 summer (Figure 4). Sites showed periods of sustained lower light levels against a trend of light levels being highest over the December to February period and then gradually declining and being higher in the southern sites than in the northern sites. These periodic low-light events, such as Lizard Island that went from a daily day-time average of 1400 μmol m^{-2} s^{-1} in mid-December 2015 to 760 μmol m^{-2} s^{-1} in late December rising back to 1300 μmol m^{-2} s^{-1} by the 10th of January 2016, correlate to periods of cloud and so represent large-scale weather systems (BoM 2016b). Heron Island saw a similar drop in average day-time light in early February 2016 with light levels on the 6th of February being half of those seen on the 27th of January. Myrmidon Reef showed a longer term drop from 1200 μmol m^{-2} s^{-1} in late February to 700 μmol m^{-2} s^{-1} for the first half of March 2016.

Comparison against satellite-derived SST measurements

SST data as L3S night-only products from the MODIS Aqua satellite (BoM 2016a) were compared to the in situ temperature data. Figure 5(a) shows data from Davies Reef where good cloud-free data were available. The correlation between the in situ and satellite data is good (Pearson correlation coefficient $r = 0.975$, $n = 104$, $p < 0.01$) with the SST data capturing some detail of the thermal spikes around the end of February 2016. A cross-plot of the two measures (Figure 5(b)) shows that the SST tends to underestimate the in situ data especially at higher temperatures. The data for Thursday Island (Figure 6(a) and (b)) show a poorer but still significant correlation ($r = 0.964$, $n = 64$, $p < 0.01$) but, due to cloud, the SST misses the major thermal anomaly that occurs in mid-March 2016 when the in situ temperatures exceed the empirical bleaching threshold (dashed line, Figure 6(a)). As with the data from Davies Reef, the SST values tend to underestimate the in situ data

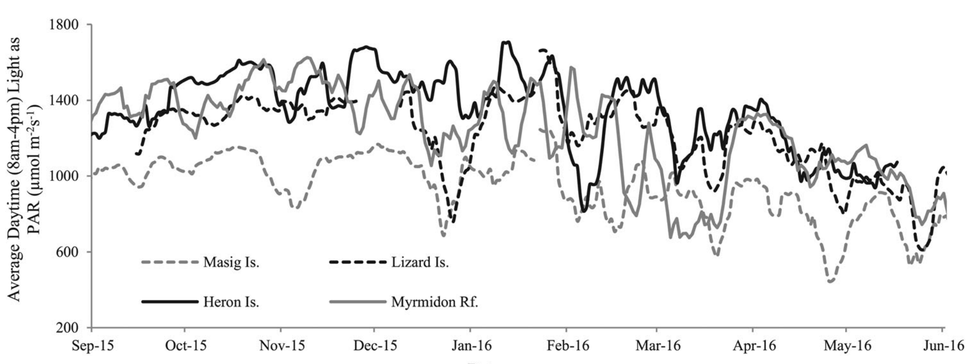

Figure 4. Average day-time (8 am–4 pm) light as PAR for Heron Island (black solid line), Myrmidon Reef (grey solid line), Lizard Island (black dashed line) and Masig Island (grey dashed line). Date marks represent the start of the month.

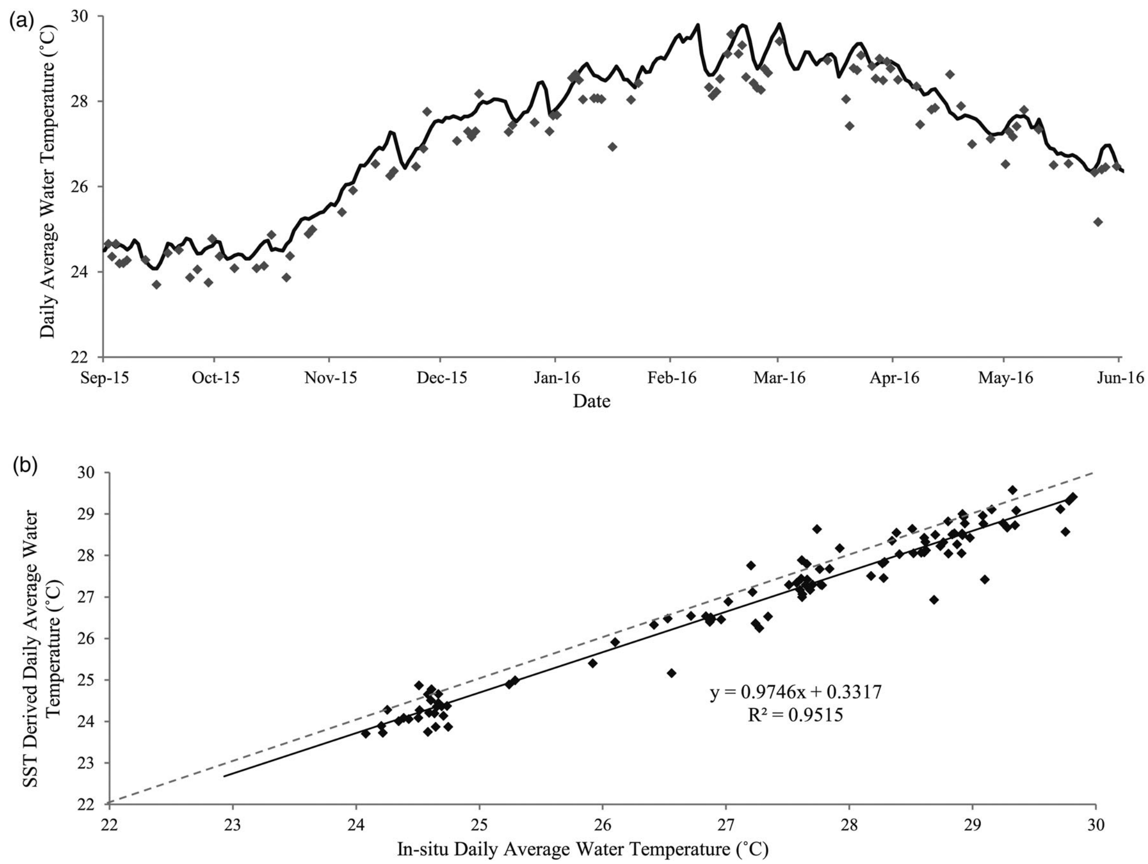

Figure 5. (a) Daily average in situ water temperature (black solid line) and satellite-derived SST (grey diamonds) for Davies Reef. (b) Cross-plot of daily average in situ water temperature (*x*-axis) and satellite-derived SST (*y*-axis) for Davies Reef. Black line shows the line of best fit, dashed grey line shows the 1:1 correspondence line.

especially at higher temperatures. Currently the SST data are being re-processed to account for new measures of bias and this may result in better correlation between the in situ and satellite data.

Discussion

Bleaching risk

The in situ observational data show that the thermal risk of coral bleaching over the 2015–2016 austral summer season on the GBR was greater in the northern part than in the south with Heron Island in the southern GBR having no days above the bleaching threshold and Thursday Island in the far north having ten days above the empirical bleaching threshold. Peak temperatures occurred later in the north (early March 2016) than in the south (early February 2016). In the north, the DHW charts show that a considerable thermal load built up rapidly from February to March. This load remained above extreme levels well into late May 2016 for both Thursday and Lizard Island.

Heron Island water temperatures remained mostly in the ±2 SD envelope and so were normal with the exception of a spike in early February. As such, with a low thermal capacitance in the system at the time of maximum temperatures, it would be expected that minor to no coral bleaching will have occurred in the Heron Island region. Davies Reef only just reached the bleaching threshold at a time when there was only a moderate heat load. Hence, from this data, some moderate bleaching would be expected in this area. Lizard Island had four days above the empirical bleaching threshold and this occurred in early March at a time where the system had a considerable thermal load. Given the co-occurrence of seasonal peak temperatures in addition to a high DHW value, widespread bleaching would be expected in this region. Thursday Island had the most extreme temperatures with peak temperatures occurring later in mid-March when the system had a considerable heat load (DHW of over 8°C-weeks) with the DHW showing the system accumulating heat with a maximum of 14°C-weeks occurring in mid-May (Figure 3(d)). As such, considerable or severe bleaching would be expected around Thursday Island reefs and the prolonged thermal load may impact survival and recovery of impacted corals. Note that Masig Island, to the north-east of Thursday Island, is typically cooler

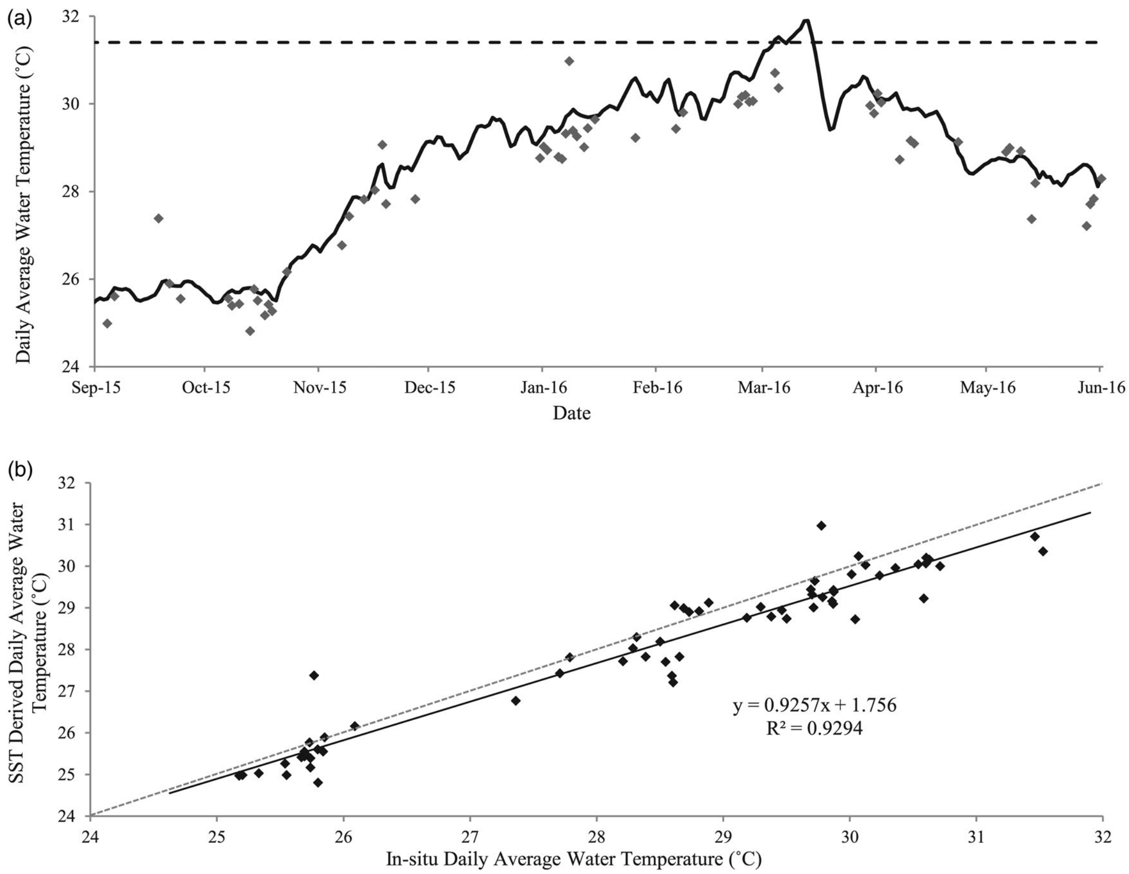

Figure 6. (a) Daily average in situ water temperature (black solid line), satellite-derived SST (grey diamonds) and the empirical bleaching threshold (dashed black line) for Thursday Island. (b) Cross-plot of daily average in situ water temperature (*x*-axis) and satellite-derived SST (*y*-axis) for Thursday Island. Black line shows the line of best fit; dashed grey line shows the 1:1 correspondence line.

than Thursday Island (Bainbridge et al. 2015) and so the bleaching risk may be most intense in the south-western and inshore parts of the Torres Strait.

Initial results from field bleaching surveys indicate a strong agreement between the observed bleaching patterns and the in situ data as contextualised by the bleaching thresholds and climatologies (GBRMPA 2016a, 2016b). The initial assessment indicates severe coral bleaching in the far north of the GBR, the area around Lizard Island having moderate to severe bleaching, the central GBR around Davies Reef having minor to moderate bleaching and the region around Heron Island only having minor bleaching. Figure 7 shows the bleaching severity for the sampled reefs within the GBR Marine Park (GBRMPA 2016b), which shows a status of minor bleaching for Heron Island and Davies Reef and severe bleaching for Lizard Island and reefs close to Thursday Island (although the report does not cover the reefs in the Torres Strait). Looking at regional patterns the bleaching severity for the reefs around the sampled reefs is shown in Figure 8 (GBRMPA 2016b), again showing a pattern of increasing bleaching going from south to north.

Post-summer warming

One characteristic highlighted by the temperature plots is an extended warming period into the late austral summer and autumn with temperatures staying above the climatology values. This pattern is particularly evident at Davies Reef, which shows late summer extended warm periods in 2014–2015 and again in 2015–2016 (grey bars, Figure 9(a)). The DHW at Davies Reef (Figure 9(b)) shows that the thermal load was high (above the 4°C-weeks limit) from March 2015 and did not return to a neutral state until October 2015. For the 2015–2016 summer the heat load was greater (peak of 14°C-weeks in June 2016) than for the 2014–2015 summer (peak of 10°C-weeks in May 2015). The 2015–2016 summer therefore saw an increased thermal load that started slightly later and lasted longer than during the previous summer. This pattern is consistent across sites, especially those in the north, and is consistent with previous El Niño events on the GBR (Lough 2007). The impact of this late summer warming on the observed bleaching and subsequent coral recovery or

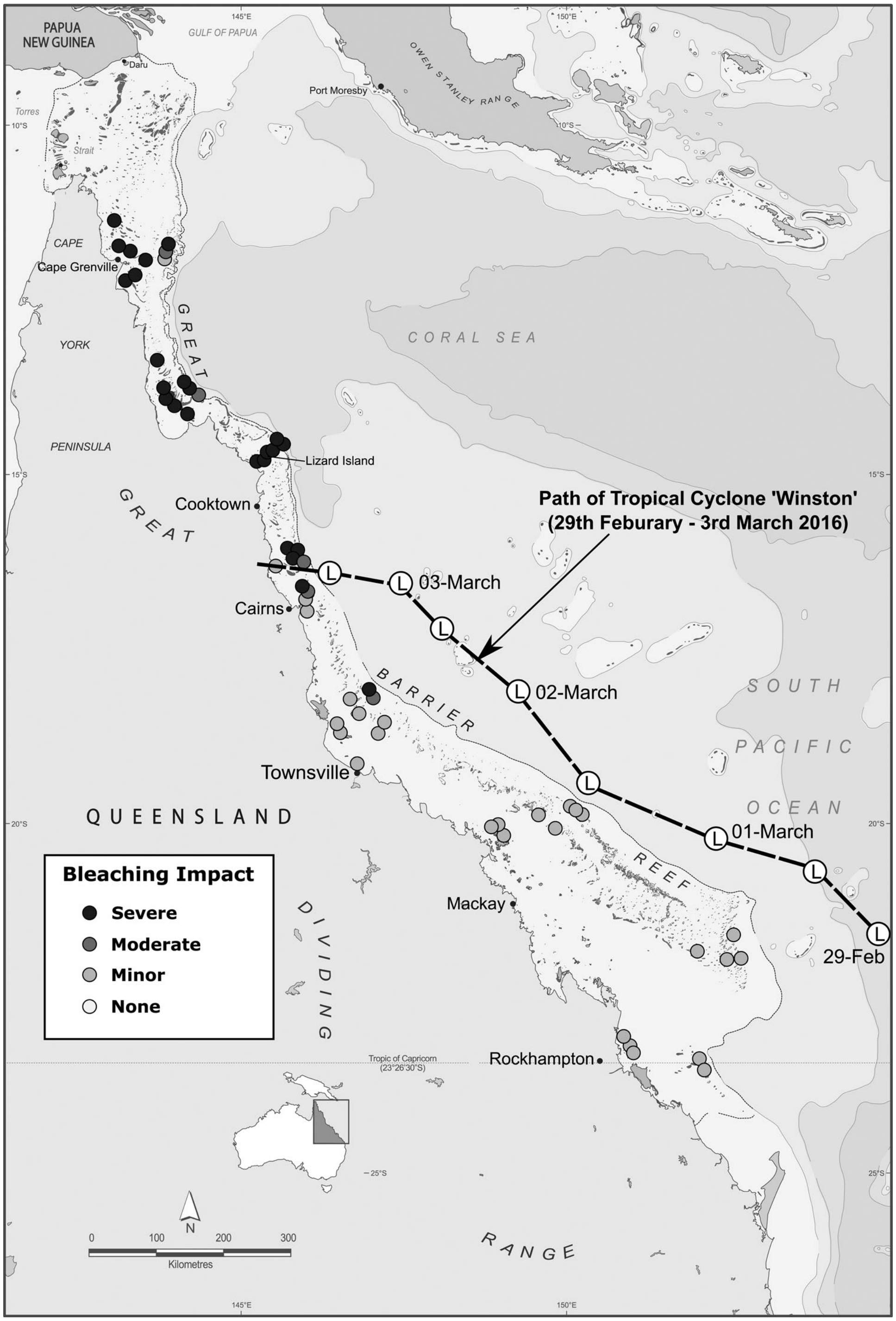

Figure 7. Map showing bleaching severity for reefs sampled within the Great Barrier Reef Marine Park (adapted from GBRMPA 2016b) overlaid with the path of Tropical Cyclone *Winston* (29 February–3 March 2016) (source BoM 2016b, 2016c).

mortality is unknown but potentially important especially given linkages between warm water events and coral disease (Bruno et al. 2007).

Causes of the observed patterns

A full analysis of the underlying causes of the observed patterns (higher ocean temperatures in the northern GBR than the southern GBR) is beyond the scope of this paper; however the 'saw-tooted' pattern of periodic temperature accumulation and cooling seen at many sites (e.g. Figure 2(a) and (b)) indicates periodic local factors act to heat and cool the water column. A co-plot of ocean temperature and average daily wind speeds at Davies Reef (Figure 10) shows that periods of heat accumulation are associated with periods of calm or

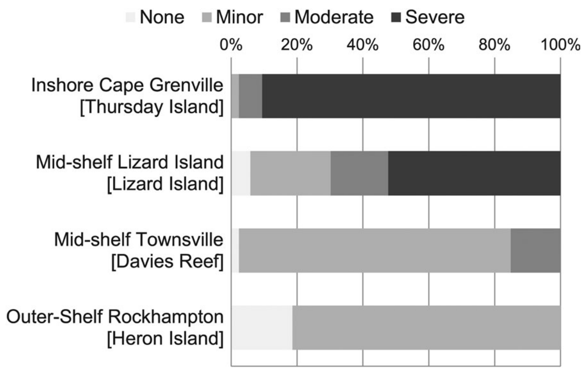

Figure 8. Percentage of reefs in each bleaching severity category for reefs in the same transect (north–south and inshore-outer shelf) as the sampled reefs (adapted from GBRMPA 2016b).

low winds while periods of heat loss are associated with higher wind events. Equivalent patterns can be seen at Thursday Island where the period of heat accumulation that lead to temperatures in excess of the empirical bleaching threshold was associated with winds less than 10 kph (Figure 11). This indicates that, at local scales, wind events driven by larger scale weather patterns work to produce heat accumulation in periods of low wind and heat loss, through wind driven mixing, during periods of higher winds (West and Salm 2003).

It is possible to trace the patterns of larger scale atmospheric processes at regional scales to the observed regional changes in light (and related cloud cover) and local scale changes in observed wind speeds. For example, the period of low wind observed at Thursday Island between late February and mid-March 2016 coincided with the passage of Tropical Cyclone (TC) *Winston* which crossed north of Cairns on the 3rd of March (BoM 2016c). The path TC *Winston* is shown as an overlay to Figure 7 with reefs to the south-west of TC *Winston* being only moderately bleached while reefs to the north-east show much higher levels of bleaching impact. The meteorological data will be further analysed to see if the data support the idea that weather systems, in this case primarily driven by TC *Winston*, resulted in conditions that cooled the southern and central GBR (via increased wind and cloud activity) but

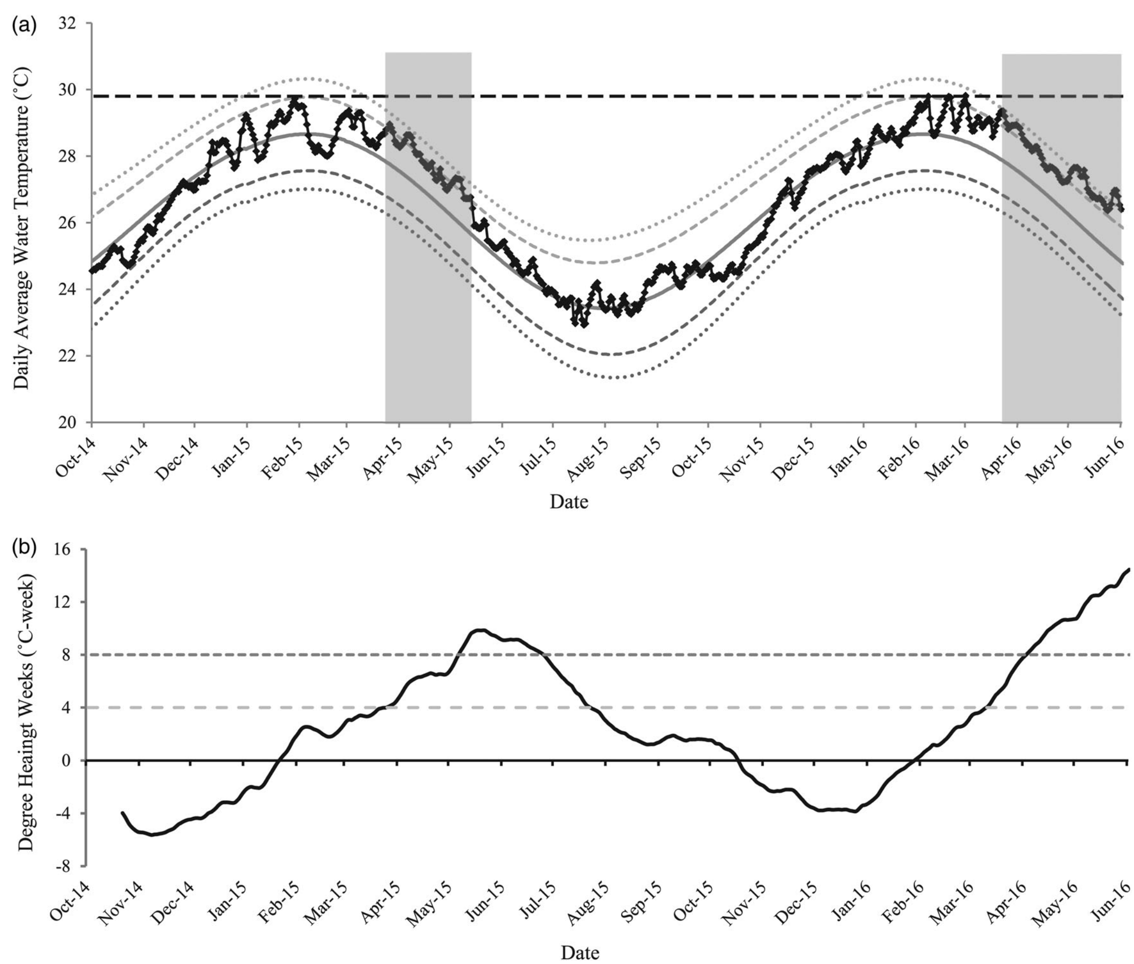

Figure 9. (a) Daily average temperatures for Davies Reef from October2014 through May 2016; legend as per Figure 2. Grey bars show periods of post-summer warming. (b) DHW plot for Davies Reef from October 2014 through May 2016, legend as per Figure 3.

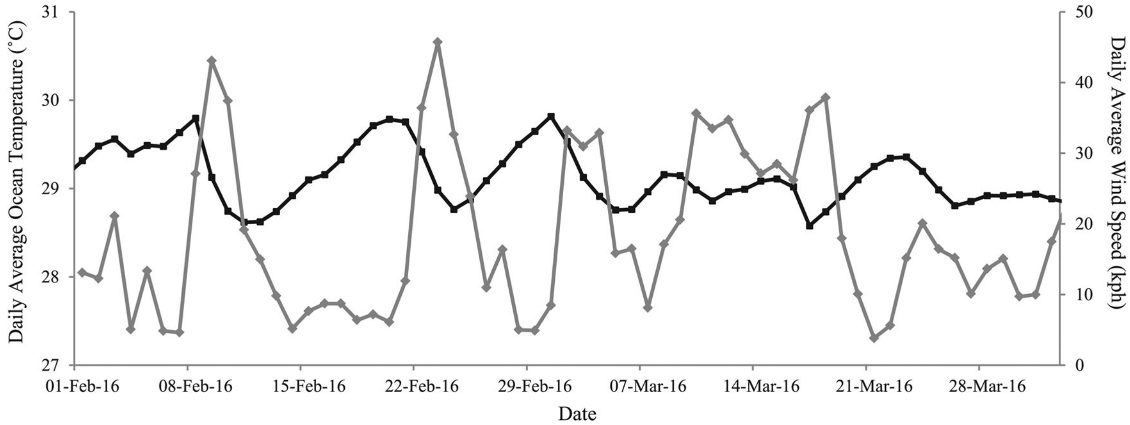

Figure 10. Daily average ocean temperatures (black line with square markers) and wind speed (grey line with diamond markers) for Davies Reef from February to April 2016. Date marks represent the start of the month.

simultaneously warmed the reefs to the north (via low wind or doldrums conditions).

Comparison against satellite-derived SST measurements

In general the correlation between the satellite-derived SST values and the in situ data was good but, due to cloud cover, the satellite data missed much of the fine-scale detail, including the thermal event at Thursday Island. The data return rates (days with data) for the satellite were 39% for Davies Reef and only 31% from Thursday Island for the study period. The other factor is the resolution of the satellite sensor, which, at 1.1 km^2, is much larger than most reef features that are made up of structural components with scales as small as tens of metres. This means that most reef-based pixels will potentially be measuring a range of water types (for example from still lagoonal water to wave-dominated reef margins). Where possible the in situ sensor was selected to match the location of the satellite pixel centre in an area where the water type could be expected to be uniform (e.g. in the middle of the lagoon at Davies Reef and in the water just off Thursday Island). Issues of cloud and spatial resolution therefore limit the ability of the satellite to discriminate the fine-scale temperature patterns seen in the in situ data; for example, the SST data missed the thermal event at Thursday Island and so would have under-estimated the bleaching risk at this site.

Conclusion

There is a strong link between environmental temperatures and coral bleaching (Brown 1997) with current concerns that coral bleaching will become more common as climate-related processes cause ocean temperatures to rise (Hoegh-Guldberg 1999). Water temperatures observed in the north of the GBR during the 2015–2016 austral summer were in excess of the empirical bleaching thresholds and the historical climate record. This matched observations of extensive and intense

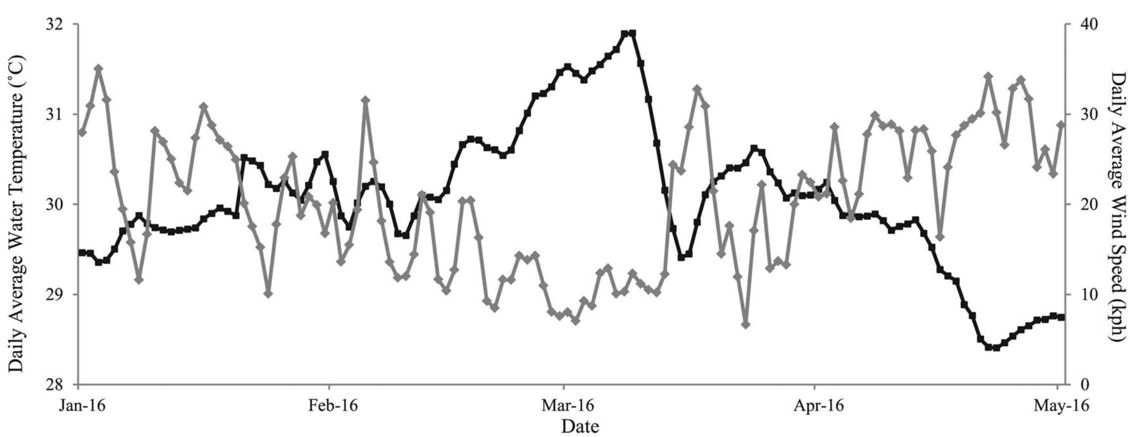

Figure 11. Daily average water temperature (black line with square markers) and wind speed (grey line with diamond markers) for Thursday Island from January to May 2016. Date marks represent the start of the month.

bleaching in the northern sector of the GBR (GBRMPA 2016a, 2016b). For the southern GBR, temperatures were close to normal and as a result little to no bleaching would be expected and only very low levels were observed. The drop in light levels observed in the central GBR points to the presence of significant weather systems, which will have played a part in moderating ocean temperatures and the resulting mixed levels of observed bleaching. Conversely high light levels and general doldrums conditions in the far north would have contributed to the observed high levels of bleaching observed in this region. As well as elevated seasonal peak temperatures the observed pattern of late summer warming, where temperatures remained 1°C or more above the climatology for a number of months, may increase the stress on corals already impacted by higher peak temperatures with implications for coral survival and recovery.

The work shows the value of real-time in situ observing systems which provided, for the 2015–2016 austral summer, daily measures of bleaching risk and stress over the summer period (AIMS 2016a), which correlate strongly with the patterns of observed bleaching (GBRMPA 2016a, 2016b) and which will provide a framework for understanding the biological responses seen along the GBR. The data collected will be analysed further to better understand the linkages between the atmospheric and ocean variables and in particular to the observed changes in light and temperature and the influence of tropical weather systems, such as TC *Winston*, on the observed in-water parameters.

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