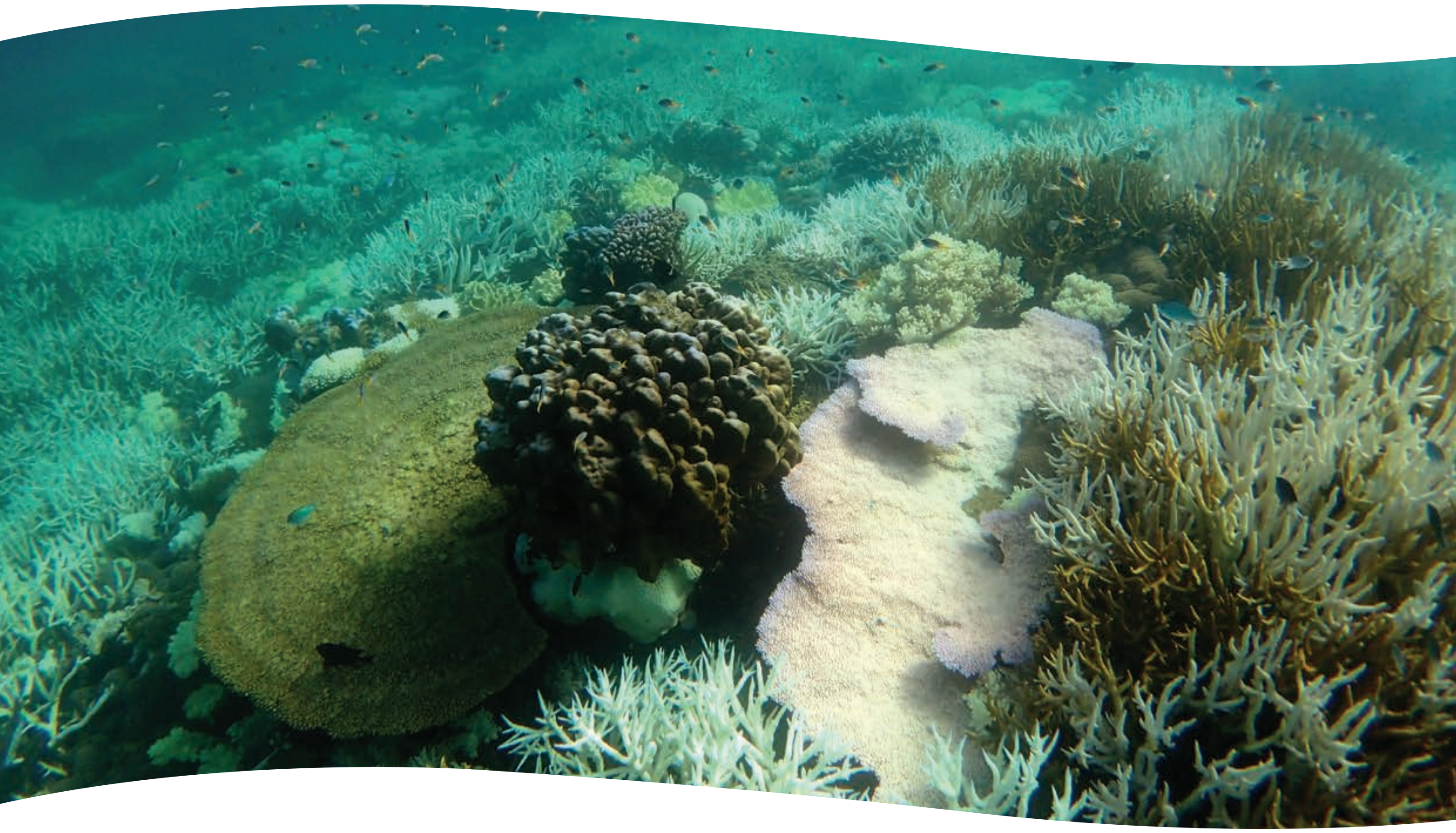
Tropical Water Quality Hub

National Environmental Science Programme

Final Report

Spatial variability in coral bleaching severity and mortality during the 2016 and 2017 Great Barrier Reef coral bleaching events

Neal E. Cantin, Eduardo Klein-Salas and Pedro Frade



Australian Government

Australian Institute of Marine Science

Spatial variability in coral bleaching severity and mortality during the 2016 and 2017 Great Barrier Reef coral bleaching events

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Cover photographs: (front) Coral reef community at Russell Island on 23 March 2017 severely bleached with recent mortality of branching and plate Acropora colonies; (back) Aerial image of a severely bleached reef community (Aerial Category 4: >60% coral cover bleached) at Potter Reef during an aerial bleaching survey on 9 March 2017. Images: Neal Cantin/ AIMS.

This report is available for download from the NESP Tropical Water Quality Hub website:
http://www.nesptropical.edu.au

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ACRONYMS

AIMS .... Australian Institute of Marine Science
AIMS LTMP .. Australian Institute of Marine Science Long Term Monitoring Program
AMPTO .... Association of Marine Park Tourism Operators
ANOVA .... Analysis of Variance
AVHRR .... Advanced Very High-Resolution Radiometer
CAT .... Category
COTS .... Crown-of-Thorns Starfish
CRW .... Coral Reef Watch
DHW …………Degree Heating Week
DCIEM .... Defence and Civil Institute of Environmental Medicine
ENSO .... El Nino Southern Oscillation
GBR .... Great Barrier Reef
GBRMP .... Great Barrier Reef Marine Park
GBRMPA ...... Great Barrier Reef Marine Park Authority
GPS .... Global Positioning System
IPCC .... Intergovernmental Panel on Climate Change
JCU .... James Cook University
JCU COE ...... James Cook University ARC Centre of Excellence for Coral Reef Studies
MMM .... Maximum Monthly Mean
NESP .... National Environmental Science Program
NOAA .... National Oceanic and Atmospheric Administration
NS .... No Significant Difference
OUV .... Outstanding Universal Values
QGIS .... Q Geographic Information System
QPWS .... Queensland Parks and Wildlife Service
RCP .... Representative Concentration Pathway
RHIS .... Reef Health and Impact Survey
RRRC .... Reef and Rainforest Research Centre Limited
SST .... Sea Surface Temperature
SSTA .... Sea Surface Temperature Anomaly
SSTAARS ..... Sea Surface Temperature Atlas of Australian Regional Seas
TSRA .... Torres Strait Regional Authority
TWQ .... Tropical Water Quality
UNFCCC .... United National Framework Convention on Climate Change
UQ .... University of Queensland
UV .... Ultraviolet

ABBREVIATIONS

e.g. .... for example
glm .... generalized linear model
i.e. .... in other words
et al. .... and others
˚C .... degrees Celsius
˚S .... degrees South

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

The 2016 and 2017 mass coral bleaching events on the Great Barrier Reef were part of the most severe, widespread and prolonged global coral bleaching event to date. Bleached corals are a clear ecosystem stress response, caused by ocean temperatures that exceed normal historical summer maximums that corals have experienced in the past. During the hot, calm conditions of a marine heatwave, corals encounter a cascade of physiological stress reactions that ultimately leads to the loss of the symbiotic algae, visible as coral bleaching, and potentially to tissue loss and whole colony mortality if the temperature stress is either prolonged for long periods or is extremely high (+2-3°C anomaly).

The widespread media coverage and reporting of the 2016 and 2017 mass coral bleaching events with conflicting reports of the extent of bleaching resulted in contradictory perceptions of the actual ecological consequences for the Great Barrier Reef (GBR). This study compiled a wide range of available bleaching observations from the Australian National Bleaching Taskforce which included researchers and reef managers from the Australian Institute of Marine Science (AIMS), JCU Centre of Excellence, University of Queensland (UQ), the Great Barrier Reef Marine Park Authority (GBRMPA), Torres Strait Regional Authority (TSRA), as well as observations from industry field management operators within the Crown-of-thorns starfish (COTS) Control team.

A total of 982 reefs (56.8% reef area of the GBR) were surveyed in 2016 and 781 reefs (50.9% reef area of the GBR) surveyed in 2017. This dataset represents the most comprehensive survey data in history, along the entire length of the GBR, including reefs in the Torres Strait.

To provide an improved understanding of the variability and the spatial impacts of coral bleaching throughout the GBR this compilation of available bleaching survey data was used to provide:

(i) a quantitative assessment of the spatial variability of accumulated heat stress, severe coral bleaching and mortality throughout the GBR on regional and within individual reef scales, in comparison with previous widespread bleaching events in 1998 and 2002; and

(ii) a quantitative comparison of bleaching observations from a range of observers which used a variety of methods and spatial assessments.

Estimates of reef area impacted by coral bleaching from aerial and in-water bleaching observations

Overall, across the entire length of the GBR, 53% of the individual reefs surveyed (representing 35% of the total GBR reef area) were categorised as severely bleached at least once during the back-to-back bleaching in 2016 and 2017. Severe bleaching (Aerial Category 4) occurred on 25% of the reefs in the Cairns to Cooktown sector, on 64% of the reefs in the Far Northern sector of the GBR in 2016 (between Cooktown and Cape York), and on 88% of the reefs in the Torres Strait in 2016. These reefs combined to account for 28% of the total reef area of the GBR in 2016.

The spatial footprint of severe bleaching (Aerial Category 4) expanded south of Cairns in 2017, as higher levels of heat stress and severe bleaching occurred on 48% of the reefs between Port Douglas and Townsville in the Northern and Central sectors of the GBR. These reefs account for 21% of the total reef area of the GBR. By the end of the back-to-back bleaching event, 35% of the total reef area of the GBR was documented with aerial and in-water surveys as severely bleached with mortality observed. In 1998 and 2002, only 2% and 6% of the reef area respectively, was documented within this severely bleached state. The spatial footprint of severe bleaching in 2016 and 2017 occurred across a much larger total reef area compared to the previous mass bleaching events documented on the GBR.

Table ES1: Proportion of the total Great Barrier Reef area surveyed (aerial and in-water surveys) that was recorded as no bleaching (Category 0), minor bleaching and no mortality (Category 1), major bleaching with low level mortality (Category 2-3) and severe bleaching with mortality (Category 4) in 1998, 2002, 2016 and 2017.

Bleaching Event	**Number of Reefs Surveyed**	**Proportion of total reef area (%) of the GBRMP and Torres Strait**			
		No Bleaching (Category 0)	**Minor Bleaching & No Mortality** (Category 1)	**Major Bleaching & Low mortality** (Category 2-3)	**Severe Bleaching & Mortality** (Category 4)
1998	495	61.5	17.7	19.2	1.6
2002	1295	49.5	21.5	28.2	0.7
2016	982	8.1	19.7	42.6	29.6
2017	781	11.0	28.6	39.0	21.4
2016 – 2017 combined	**1131**	**4.8**	**20.6**	**39.6**	**35.0**

Note: 2016-2017 combined total represents unique reefs using the highest bleaching category in either year, excluding duplicate reefs with a lower score between years resulting in the total percentage of reef area that reached each bleaching category in either 2016 or 2017.

Coral bleaching severity in deep reef environments (6.1 – 40m) ranged from 20-90% in 2016 and from 25-75% of the coral community in 2017. On average, deep reef habitats from transect based methods exhibit an average reduction in the proportion of the coral community bleached by 32.5% (2016) and by 9.2 % (2017) at a Degree Heating Week (DHW) >8 and by 14.8% in 2017 at a DHW 5-8, compared to shallow reef habitats at the same level of heat stress.

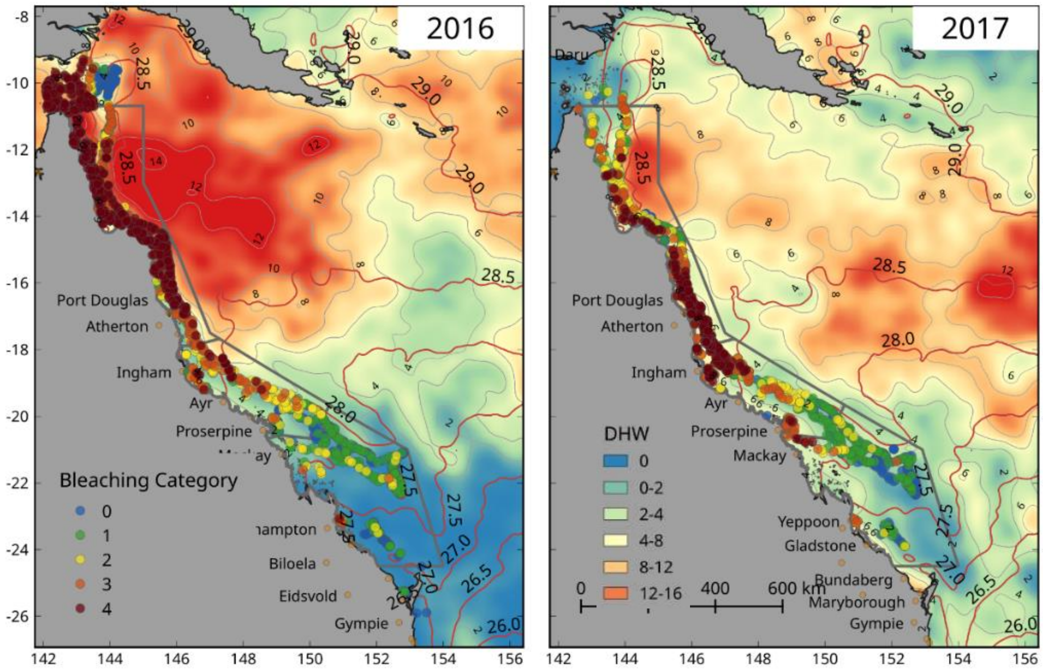


Figure ES1: Spatial distribution of aerial and in water bleaching survey observations in 2016 and 2017 along the entire length of the GBR. DHW values from 0-2: no bleaching (ie. normal summer conditions), 2-4: possible bleaching, 5-8: severe bleaching and some coral mortality, >8: extreme bleaching and widespread mortality likely. Community level (combined hard and soft corals) bleaching severity categories: 0 = no bleaching (>1%), 1 = minor (1-10% bleached), 2 = moderate (10-30%), 3 = major (30-60%) and 4 = severe (>60%).

Severity of the event: Bleaching and mortality thresholds

During the 2016 - 2017 bleaching events, both coral bleaching and coral mortality occurred at a lower level of accumulated heat stress than previously proposed by the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch (CRW) Degree Heating Week (DHW) product. The combined data recorded widespread coral bleaching occurring at a NOAA DHW value of 2-4 degree-weeks, severe bleaching, and some coral mortality at 5-8 DHW's, and extensive mortality at reefs exposed to more than 8 DHW's.

Prior to this event, the general guideline based upon previous observations was that coral bleaching would occur at a DHW >4 and that coral mortality would begin at a DHW >8.

Coral mortality due to thermal stress ranged from 1.9% - 97.8% from all in-water surveys during the 2016 - 2017 summers. Coral mortality at the reef population level across the GBR from all in-water surveys (median response) was 3.2% at a DHW 2-4, 6.9% in 2016 and 6.6% in 2017 at a DHW 5-8 and 14.5% in 2016 and 15.8% in 2017 at a DHW >8. Including the proportion of the reef corals recorded as severely bleached and the recently dead colonies combined at the peak of heat stress (Bleaching State 5 + 6), 33.1% (DHW 5-8) and 15.9% (DHW>8) in 2016 and 29.9% (DHW 5-8) and 50.0% (DHW>8) in 2017, of the reef community is at risk of mortality during the recovery period in the months following maximum peak heat stress.

Estimates of the total reef area impacted by extreme heat anomalies leading to coral bleaching

Even though this was the largest bleaching event recorded to date on the GBR, observations of coral bleaching during the 2016 and 2017 events did not impact all corals on all GBR reefs. To scale up estimates of bleaching to the whole GBR (including both surveyed and not surveyed reefs), we combined the broad spatial coverage of satellite Sea Surface Temperature (SST) monitoring products (NOAA Coral Reef Watch) with the established relationship of observed bleaching severity with the accumulated heat stress product NOAA Degree Heating Weeks (DHWs).

Table ES2: Proportion of the total Great Barrier Reef area that was exposed to a level of accumulated heat stress (NOAA Degree Heating Week version 3.1) capable of causing no bleaching (DHW 0-2), minor bleaching and low/no mortality (DHW 2-4), major bleaching and some mortality (DHW 5-8) and severe bleaching and extensive mortality (DHW>8) in 1998, 2002, 2016 and 2017.

Bleaching Event	Total Reef Area (%) of the GBRMP and Torres Strait			
	DHW 0-2	**DHW 2-4**	**DHW 5-8**	**DHW>8**
1998	75.7	20.3	3.9	0
2002	49.6	35.5	14.5	0.4
2016	35.4	15.3	20.9	28.3
2017	9.4	27.7	35.8	27.1
2016-2017 combined	**8.0**	**25.0**	**21.7**	**45.2**

Note: 2016-2017 combined total represents unique reefs using the highest DHW category in either year, excluding duplicate reefs with a lower DHW accumulation between years resulting in the total percentage of reef area that reached each DHW category in either 2016 or 2017.

When comparing the recent bleaching event in 2016 - 2017 to the previous mass bleaching events on the GBR, a significant increase in the spatial footprint and the duration of extreme accumulated heat stress and levels of severe bleaching and coral mortality is apparent. In 1998, no GBR reefs were exposed to a DHW >8 (equivalent of >2 months above a normal summer maximum temperature). In 1998 and 2002, only 18% of the reef area was documented as major or severely bleached and coral mortality due to bleaching was low. At the end of the back-to-back bleaching events of 2016 and 2017, 45% of the total reef area was exposed to extreme heat stress (DHW > 8), with reefs at this level of heat stress resulting in 51% of the coral community (median) dead or dying (Bleaching State 5+6, severely bleached).

The intensity and duration of the heat anomalies in 2016 and 2017 were record-breaking and unlike the other two past recorded regional mass bleaching events on the GBR. Balanced messaging and a unified communication strategy are essential components to reducing unnecessary controversy surrounding the impacts of this, and future, marine heat waves on the GBR. The GBR is a very large ecosystem, which results in large variations in heat exposure, bleaching response and subsequent mortality to the coral reef communities.

This report combined all available bleaching observations to assess the full impact of the recent marine heat wave, by quantitatively assessing the spatial footprint of both thermal exposure and bleaching-related mortality throughout the GBR. The analyses clearly showed that simplistic messages suggesting "the GBR is dead" were incorrect and do not reflect the actual impact of the event. Similarly, statements of little to no loss of living coral were also incorrect. Reporting coral bleaching impacts of a particular reef or region would best be provided within the context of the expected level of impact given a location's actual accumulated heat stress and coral community composition before and after the event. A single reef does not represent the entire GBR.

The GBR is the world's largest coral reef ecosystem. Consistent and repetitive ecological survey techniques are required to truly understand the full scale of the impacts of marine heat waves. During the progression of a bleaching event over weeks to months the level of impact will change within a single reef over time and between regions along the length of the GBR as the spatial footprint of heat stress increases and the bleaching response develops. Conversely, local or regional weather events may lead to a temperature reduction and, hence, mitigation of the corals' stress response.

1.0 INTRODUCTION

Corals have become successful reef builders in clear, tropical waters because of the symbiotic relationship with a single celled dinoflagellate alga, called *Symbiodiniaceae (*zooxanthellae). The algal symbiont uses sunlight to photosynthesize and provide the coral animal host with photosynthates (sugars) that fuels the energetic demands of daily metabolism, reproduction, skeletal calcification, and tissue growth. This symbiosis performs at its best 1-2˚C below the typical local summer maximum temperature. During hot, calm (low wind, lower water flow and low wave energy) conditions during a summer heatwave, the high light environment combined with higher than normal ocean temperatures degrade the enzymes that drive the photosynthetic processes (Jones et al. 1998). As the photosynthetic electron transport chain breaks down during heat stress, the symbionts continue to absorb light energy that can no longer contribute to photosynthesis, which then generates toxic reactive oxygen that becomes harmful to the coral animal, as protective mechanisms that normally dissipate excess light begin to fail (Jones et al. 1998). As this bleaching response unfolds, the coral host breakdown the symbiosis and expel the symbiotic partner in an attempt to protect its own cellular tissue from further oxidative damage (Fitt et al. 2001). When the coral animal loses its symbiont population, the brown-green algal cell densities decrease to the point that the white, limestone skeleton becomes visible through its clear tissue. Corals can bleach and turn white from a range of stressors (e.g. low salinity from freshwater flood plumes, herbicide exposure, cold temperatures), but it is the heat driven widespread mass bleaching events across regional spatial areas, not just one coral or one reef, that is of concern from an environmental impact perspective.

Corals are a sensitive indicator for revealing the effects of 0.8-1.0˚C of ocean warming because this symbiosis can only withstand a short-term exposure outside the normal thermal range for each individual location. As ocean temperatures exceed the historical average summer maximum upper thermal limit more often and for increasingly prolonged periods of time, the spatial footprint of mass community and ecosystem level bleaching responses has increased. Consequently, there has been significant attention and coverage of the bleaching events from reef managers, science communities, tourism and industry sectors through both popular media channels, public reporting and peer-reviewed journal publications. The recent heat waves in 2016 and 2017 were unprecedented for the GBR. Temperatures remained above historical summer maximums for more than three months, and maximum anomalies in some locations were as high as 2.9˚C (2016) and 3.2°C (2017) above the recent historical average summer maximum (1985-2012). Here we compile a wide range of available bleaching observations to assess and communicate the spatial variability of coral bleaching and how this relates to the current state of the GBR.

1.1 Perspectives of the 2016 - 2017 GBR coral bleaching events

The 2016 and 2017 GBR bleaching events were a regional component of the widest, most prolonged global coral bleaching event to date. This was the third global event on record to impact coral reef ecosystems across all three ocean basins. More than 70% of the world's coral reef locations were exposed to bleaching-level heat stress (Heron et al. 2017). Bleaching began in 2014 in Guam and the Commonwealth of the Northern Mariana Islands. It then progressed throughout the North Pacific to parts of the Northwestern Hawaiian Islands, the

Marshall Islands and the main Hawaiian Islands, during the intensification of the strongest El Nino on record which fully formed in 2015-16. The El Nino Southern Oscillation (ENSO) induced warming then brought heat stress bleaching and mortality to Florida, Papua New Guinea, Fiji, Australia's Great Barrier Reef, some Western Australia reefs (Gilmour et al. 2019), Chagos Archipelago, the western Indian Ocean, Seychelles, the Red Sea and western Indonesia in 2016.

This global event concluded with the GBR bleaching again during the weak La Nina phase in 2017, a 3-year progression of coral bleaching throughout the tropics. Several locations experienced repetitive back-to-back bleaching in consecutive years for the first time, including Guam in 2013, 2014, 2016 and 2017 (Raymundo et al. 2019), Chagos Archipelago in 2015 and 2016 (Head et al. 2019) and the GBR in 2016 and 2017. Catastrophic bleaching related mortality was observed in the Northern Line Islands of the South Pacific with >98% mortality causing coral cover to drop from 18% to 0.4% across a wide depth range from the shallows (0-6m) to deep reef slopes (18-25m) (Vargas-Ángel et al. 2019). (See Eakin et al. 2019 for a full global review).

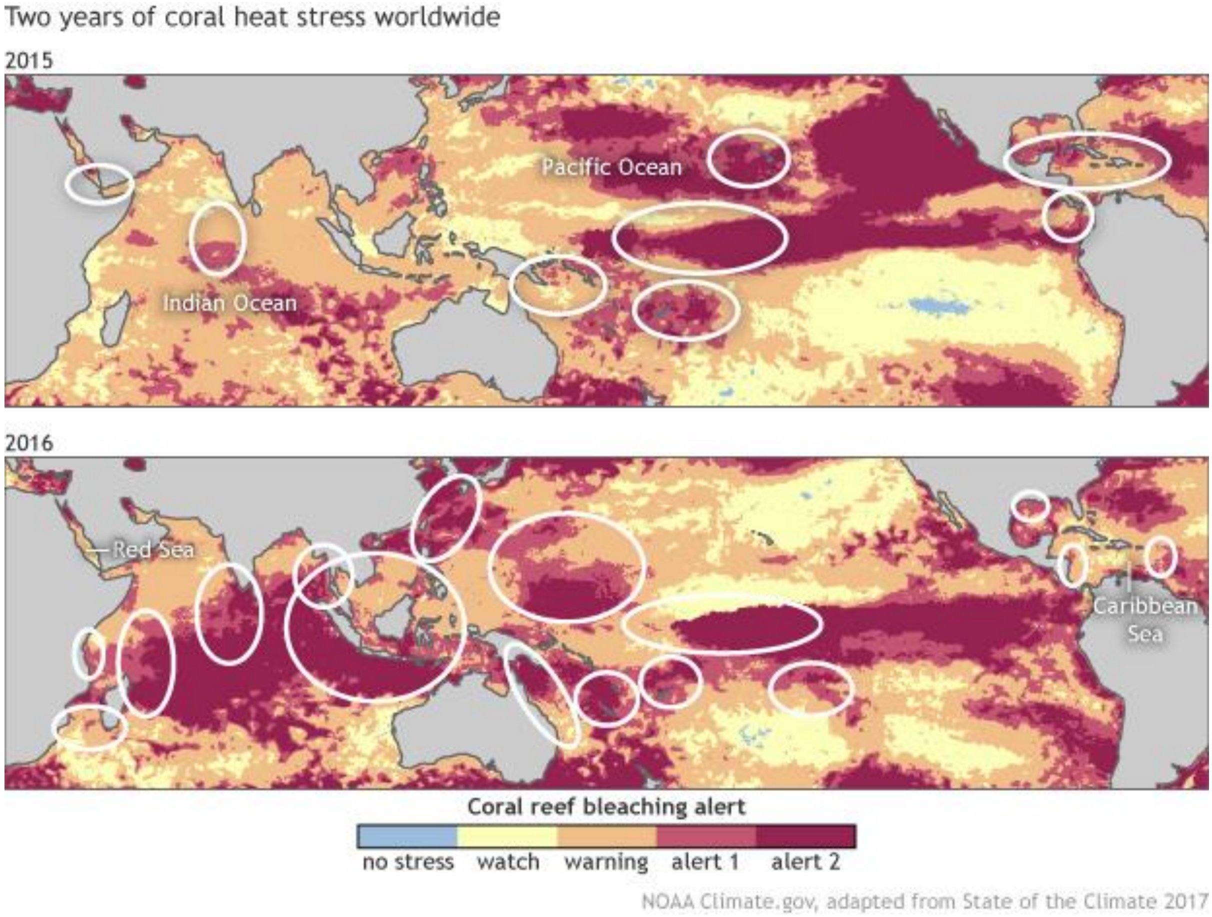


Figure 1: Development of heat stress in 2015 and 2016 during the third global mass bleaching event of 2014-2017. No stress in this image would represent temperatures at or below the historical summer average (Maximum Monthly Mean (MMM); 1985-2012) for each individual location, which did not occur within any coral reef region (white circles). Watch = temperatures exceeding the MMM but below the NOAA Degree Heating Week (DHW) MMM+1˚C threshold; Warning = temperatures at least +1˚C for 0-4 weeks; Alert 1 = temperatures temperatures at least +1˚C for 4-8 weeks likely to cause bleaching; Alert 2 = extreme prolonged temperatures at +1˚C for >8 weeks and likely to result in mortality. (image and data from NOAA Coral Reef Watch (Eakin et al. 2018)).

BOX 1 An individual reef does not define the status of the entire Great Barrier Reef ecoystem

(A)

(B)

Photos of an individual reef within the Great Barrier Reef after the 2016 - 2017 bleaching event can easily be used to communicate very different perceptions of the current status of a very large coral reef ecosystem. The truth is, across an ecosystem that is 2,000km long, and comprised of over 3,000 individual reefs and 900 islands that support fringing reefs, variability of coral reef community impacts (from no bleaching healthy reefs to 98% mortality of all coral growth forms) must be expected. **(A)** A healthy, diverse reef flat in the Far North of the GBR (Reef 10-416) located on the outer shelf edge in November 2017; a reef that avoided bleaching impacts and presents one of many prime examples of why the GBR remains an icon even after the bleaching event; **(B)** A heavily impacted reef at Dugong Islet (only ~120km west of Reef 10-416), that suffered extensive mortality of virtually every growth form, including long-lived, massive Porites colonies leaving graveyards of dead, overgrown coral skeletons behind. The overall goal for coral reef stakeholders (scientists, managers and tourism operators) needs to remain a balanced communication strategy, which captures the current status of the GBR as a whole, not just local individual snapshots which convey a controversial outlook. Images were collected November 2017 (Images: – (A): Neal Cantin (AIMS), (B): Zack Rago).

1.2 Is the Great Barrier Reef dead?

Documenting disturbance events like coral bleaching and severe cyclones, is an important component of the scientific evidence base to provide context and attribute the source of impacts within monitoring trends that reflect the condition of coral reef ecosystems. The widespread media coverage and reporting of the 2016 and 2017 mass coral bleaching events with conflicting reports of the extent of bleaching resulted in contradictory perceptions of the actual ecological consequences for the GBR. While globally a perception was that the GBR was dead, locally it was perceived to have only sustained minor damage by some (Eagle et al. 2018).

Given the iconic nature of the GBR and the livelihoods of so many Australians dependent upon this natural and threatened coral reef ecosystem, capturing and communicating the reality and the overall level of impact of change to the ecosystem is critical. Developing an effective and balanced communication strategy remains of high priority for the future but requires balanced accurate representation of the reality as documented by quantitative observations and considering the GBR in its entirety. Natural iconic locations, like the GBR, have become an effective strategy to increase public awareness and engagement in environmental degradation, to drive behavioural change that will reduce the impacts of climate change (Curnock et al. 2019), particularly when major disturbance events impact upon the state of the environment. However, scientific reporting, environmental conservation messaging and mass media coverage of the impacts caused by natural disasters is often accompanied with a cost to reef stakeholders (e.g. tourist operators) that are dependent upon the perceived state of the reef for successful economic returns, livelihood and the cultural values that are placed upon the health and status of the GBR.

In this report, a wide range of available bleaching observations from reef stakeholders, including scientists, tourist operators and management authorities to compare, contrast and investigate the spatial severity of severe coral bleaching and bleaching related mortality of living coral along the entire length of the GBR has been compiled.

This report provides a quantitative assessment of the impacts of the 2016 and 2017 heat wave to quantify to the total reef area within the Great Barrier Reef Marine Park (GBRMP) that was impacted by coral bleaching and bleaching related mortality. First, all available aerial and in-water bleaching observations to quantify the relationship between coral bleaching and accumulated heat stress from ocean SST products and bleaching severity and coral mortality. Second, this relationship from the 56% of reef area with documented bleaching severity observations to the entire GBR was extended, to provide a quantitative estimate of the total area of reef that was bleached, severely bleached and predict the mortality throughout the entire GBR based on the spatial footprint of accumulated heat stress. When corals are exposed to a level of accumulated heat stress in these upper categories (DHW 5-8 and >8), ecosystem shifts from reef building coral dominated habitats to algal dominated systems due to coral mortality are likely as a direct result of ocean warming. Third, a comparison of records of the previous mass bleaching events in 1998 and 2002 to the recent 2016 and 2017 back-to-back bleaching events to provide a perspective of how the spatial footprint of heat stress, bleaching and bleaching related mortality has increased in a relatively short period of time (14 years) was made. The presentation of all available observations during the 2016 - 2017 event will attempt to provide clarity to highlight both sides of the story; individual reefs and regions that avoided severe bleaching and the increasing number of reefs that suffered mortality causing degradation to iconic GBR ecosystem services.

2.0 METHODOLOGY

Coral bleaching datasets have been collected from a wide range of reef stakeholders to document and compare the spatial severity of coral bleaching throughout the GBR. Data include aerial and in-water observations from the scientific community contributing to the National Bleaching Taskforce (JCU COE, AIMS, TSRA, UQ, Catlin Surveys), from GBRMPA field management bleaching response, QPWS rangers and the COTS Control Program. (See Appendix 2 – Data Sources for detailed access and dataset descriptions).

2.1 Bleaching survey methods

2.1.1 Aerial bleaching surveys

Broad-scale aerial surveys are an effective and rapid method for documenting coral bleaching at as many representative locations as possible across large-scale marine ecosystems. The time available to capture the community bleaching response at its peak is short. Within a period of 2-3 weeks, severely bleached corals can become overgrown with turf algae and no longer visible from the air. Compiled aerial bleaching survey datasets from 1998, 2002, 2016 and 2017 were conducted from a combination of light fixed wing aircraft and helicopter, flying at an elevation of approximately 150m. This method accurately captures the proportion of healthy and bleached coral colonies in the shallow reef flat (0-3m) and in the upper reef slope (0-6m). Reefs were scored independently (isolated communications) by 2-4 observers looking out the left and right windows of the aircraft. Bleaching scores were recorded on spatial GBRMPA zoning reef maps, with mapping handheld GPS devices recording the flight path and confirming the reef location during the flight (Berkelmans & Oliver 1999; Berkelmans et al. 2004; Hughes et al. 2017).

Surveys in 1998 and 2002, did not have GPS recorders (pers. comms, R. Berkelmans). Reefs were categorised by visual assessment based upon the proportion of living coral visible to the observer that appeared bleached, severely bleached white, or fluorescent (Figure 4), into five community bleaching severity categories:

- **0** (no bleaching) <1%,
- **1** (moderate) 1-10%,
- **2** (high) 10-30%,
- **3** (very high) 30-60%,
- **4** (extreme bleaching) > 60%;

These categories were used to align with the protocols developed in 1998 by Ray Berkelmans and GBRMPA (Berkelmans & Oliver 1999; Berkelmans et al. 2004). Photographs of each categorised reef in 2016 were recorded, stored, geo-located with GPS locations and made available to the public through the JCU Centre of Excellence for Reef Studies website (https://www.coralcoe.org.au/coral-bleaching-map). Images from the GBRMPA flight in 2017 between Townsville and Cairns will be available through the eAtlas. Recently dead coral colonies can be seen from the aerial images at severely impacted sites (Figure 2), although this level of detail was not recorded.

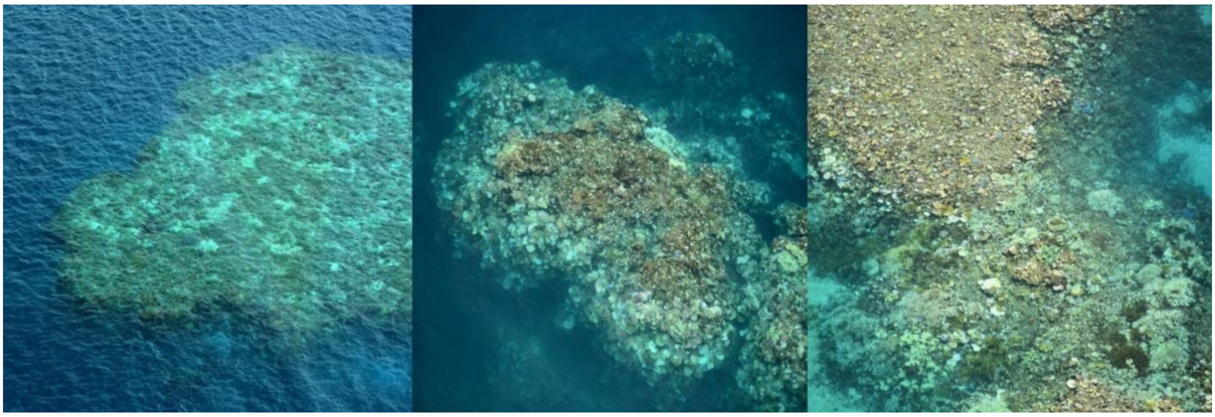


Figure 2: Aerial survey images from 9 March 2017 showing a category 0 no bleaching reef (Left Panel) and category 4 (>60% of the community severely bleached) reefs (middle and right panels). Severely bleached corals that are completely white and/or fluorescent blue, pink and yellow are easily identified from the air. Recently dead colonies becoming covered in fresh green and brown turf algae are also detectable (Right Panel). (image credit: Neal Cantin and Sam Noonan – AIMS).

2.1.2 In-water quantitative transect based surveys

In-water surveys were conducted between Townsville and Port Douglas by the AIMS at 54 sites within 19 reefs in 2016 and 40 sites within 12 reefs in 2017, from 13 March – 6 April, 2016 and from 14 March – 1 April, 2017. Surveys were conducted following the onset of maximum temperature exposure to capture the bleaching response at its peak, with an additional 0 – 2.9 DHW accumulating following the time of the survey. Follow up surveys were conducted in June 2016, September 2016 and September 2017 to assess survivorship. For each reef, surveys were conducted at three habitats:

(1) shallow, sheltered reef flat at 2m;
(2) exposed shallow reef slope at 3m; and
(3) deeper exposed reef slope at 7-9m along permanent AIMS Long-term monitoring sites or equivalent on the northern exposed flank of each reef.

The use of these long-term permanent sites allows us to detect changes in coral composition directly related to coral bleaching. Five 10 x 1m belt transects were conducted with 1 x 1m images captured along the length of the transect for image analysis. Observers identified and counted each coral colony (hard and soft corals) >5cm in diameter and recorded a categorical bleaching score for each individual based on the proportion of the colonies tissue visual bleaching state (% individual colony area that was bleached white):

(1) no bleaching (Figure 3A);
(2) minor-moderate **(**1-50%); (Figure 3B);
(3) major (50-95%; Figure 3C);
(4) severe **(**95-100% bleached white or fluorescent (Figure 3D); and
(5) bleached with complete or partial sections of the colony recently dead (Figure 3E).

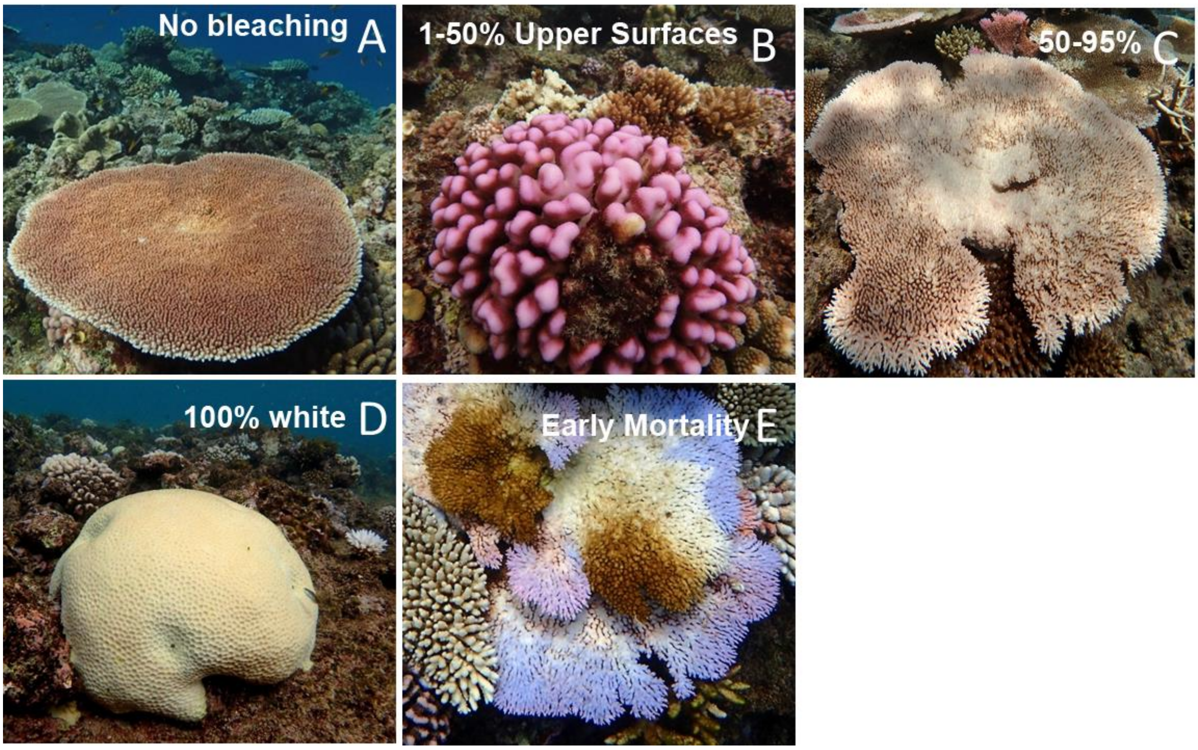


Figure 3: In-water survey individual colony bleaching severity categories referred to as a bleached state. (A) Bleached State 1: No bleaching, (B) Bleached State 3: 1-50% colony area bleached, usually upper surfaces, (C) Bleached State 4: 50-95% of the colony area bleached, (D) Bleached State 5: 100% white severely bleached (with or without fluorescent pigments) and (E) Bleached State 6 - Bleaching related recently dead colonies (full colony or partial sections of the colony).

In water surveys conducted by the University of Queensland Global Change Institute (Frade et al. 2018) were conducted between 14 - 23 May, 2016 at nine sites within six outer shelf reefs in the Northern Sector of the GBR, at a depth of 5, 10, 25 and 40m, in order to determine the effect of bleaching over a large depth range. Surveys were conducted along 1m belt transects covering 75m length at each depth. Scleractinian hard corals >10cm in diameter were identified to genus level and bleaching severity categorised as: (1) healthy; (2) minor bleaching (paling/ 1-50%; (3) severely bleached (51-100% bleached) and (4) recently dead.

2.1.3 In-water qualitative Reef Health Index Surveys (RHIS)

In water surveys conducted by the GBRMPA field management team in 2016 were conducted at a total of 62 reefs across seven inshore-offshore transects following guidelines outlined in the Coral Bleaching Risk and Impact Assessment Plan (GBRMPA 2011). Surveys used in this report were performed from March to June 2016. These transects included reefs throughout each latitudinal reef management zone from north to south, perpendicular from the coast of Cape Grenville (approximately latitude 11°S), Princess Charlotte Bay (latitude 13°S), Lizard Island (latitude 14°S), Cairns–Port Douglas (latitude 16°S), Townsville (latitude 18°S), Whitsunday Islands (latitude 20°S) and Rockhampton (latitude 22°S) (For full details see GBRMPA 2011, 2017). The survey plan aimed to conduct 15 or more Reef Health and Impact Surveys (RHIS) (that is, replicate samples) across three different locations on each reef, corresponding to three different aspects (north-east, north-west and south-west). At each of the western locations (i.e. north-west and south-west), three RHIS surveys were conducted at the same depth (approximately one to four metres), making a total of six RHIS. At the northeastern location, three surveys were conducted at three different depths (approximately one to three metres, six metres and nine metres), making a total of nine RHIS. Surveys followed the standard protocol for Reef Health Impact Surveys (RHIS) (Beeden et al. 2014). Key information recorded includes:

i) qualitative estimates of the percentage of the benthos (sea floor) made up by macroalgae, live coral, recently dead coral, live coral rock, coral rubble and sand; and
ii) observations of coral impacts, and this is done over a series of five-metre radius point surveys (with one RHIS form completed for each circular plot of 78.5 square metres).

The percentage of coral cover (if any) that had recently died from each impact-type (that is, bleaching, disease, predation, damage) was estimated as described in Beeden et al. (2014) for each RHIS survey by examining all coral colonies within the point surveys for any impacts. These data were used to categorise the percentage of bleached corals within the total living coral within each RHIS area. For comparison to all aerial survey data and the in-water transect based quantitative estimates, the average RHIS per cent bleached scores for each reef were converted to align with the aerial bleaching categories described above (Berkelmans et al. 2004).

In-water surveys conducted by the COTS Targeted Control Program were also collected for this analysis from the Eye on the Reef Program from 2016 and 2017 (RRRC and AMPTO 2016). Three RHIS surveys were conducted at each reef and followed the standard protocol for RHIS (Beeden et al. 2014), recording the percentage of bleached corals among the living coral cover in addition to records of coral cover, coral type and potential COTS presence, absence and damage. Bleached corals were categorised according to the GBRMPA Coral Bleaching Response Plan (GBRMPA 2011) among four RHIS Colony bleaching levels:

(1) upper surfaces
(2) Pale/Fluoro
(3) Totally white
(4) Recently dead.

2.2 Heat stress metrics in coral reefs that predict coral bleaching

Historical average maximum temperatures (climatologies) are a key feature in predicting summer extremes and are used to define anomalies that exceed the normal summer maximum that a reef historically experienced. Deviations above the historical summer maximum, for prolonged periods will put corals at risk of thermal stress and bleaching. Using daily 5km (0.05˚ resolution) satellite remote sensing data from the NOAA CRW Version 3.1, the annual SST anomalies from 1985-2018 were assessed. The NOAA Degree Heating Week product is a thermal stress index which combines the intensity of the temperature anomaly (Hotspot) at least 1˚C above the historical summer Maximum Monthly Mean (MMM, Version 3.1) temperature (upper thermal threshold) with the duration of time exceeding this threshold over a 12 week period. A heat stress accumulation of four DHWs, essentially represents a reef experiencing 1 month at 1˚C above a normal summer maximum or two weeks at 2˚C above a normal summer maximum (Liu et al. 2003). Guidelines based on past bleaching events predicted that at a DHW values from 0-4: no bleaching (ie. normal to just above average summer conditions), 4-8: possible bleaching, >8: extreme bleaching and widespread mortality likely (Liu et al. 2003).

2.3 Data analysis

All in-water bleaching observations were converted to align with the National Bleaching Taskforce aerial bleaching categories 0-4 (Section 2.1.1). For community level bleaching response, transect and RHIS based observations were converted into a percentage (%) bleached of all corals counted from the survey method, which was then converted into the 5 category scale used by the aerial survey scores (Section 2.1.1). The in-water and aerial bleaching observations to establish the relationship between total heat stress accumulation (DHW) and the overall coral community level bleaching response (% of living corals bleached) were combined. The in-water transect (Bleached state 5 and 6; Section 2.1.2 Figure 3D and 3E) and RHIS (RHIS Bleached Category 3 and 4; Section 2.1.3) were combined to provide estimates of the proportion of individual coral colonies that were severely bleached or recently dead.

To summarise the bleaching condition of any individual reef, only surveys performed after 15 February up to 1 May were considered for each year, to ensure that the reported bleaching severity followed the peak onset of warming. For reefs that include more than one survey during the same year, the bleaching response for any individual reef was summarised using the 75th percentile of the distribution all the surveys completed at that reef for each year. This avoided the impact of any remaining very low-value bleaching metrics on a central value (like the mean). The selected quantile provided a relatively high weight to the upper values of the bleaching response. However, other quantiles (mean and median) were also evaluated and presented in figures.

All surveys were allocated into two depth categories according to its reported depth: shallow (<=6m) and deep (>6m), as deeper surveys (from 10-40m deep) were available only for a limited number of reefs. Aerial surveys were always considered as shallow, even if they represent an integrated characterization of the visible depth range in the water column.

The maximum heat stress for every 0.05°-pixel over the GBR for each year (DHWmax) was obtained from NOAA's CRW and categorised following the classification of Lui et al. (2003) with additional classes: 0, 1-2, 3-4, 5-8, >8 degree-heat-week. The DHWmax were assigned to every individual reef using the reef's centroid coordinates (from GBRMPA GBR features layer).

To estimate the GBR wide potential impact of this bleaching event at reefs without surveyed bleaching severity observations, a binomial generalized linear model (glm) for proportional data from the relationship between the bleaching response (% community bleached, % severely bleached (Bleached State 5), % mortality (Bleached state 6) and combined severely bleached and recently dead (Bleached State 5+6) and the total heat stress accumulation (DHW) was developed. This predictive glm was developed from only the transect based in-water bleaching observations due to the wide variability observed from the RHIS based observations across the full range of DHW. Years were pooled for the glm since the transects available in 2017 did not contain observations at reefs with a DHW exposure <5. A glm modelling framework (R, glm from stat package version 3.6.3), including depth of survey as a fixed factor (shallow/deep), and included an adjustment for the timing of survey in relation to the date at which maximum DHW (max.DHW) accumulation occurs at each individual location. If the survey occurs after the max.DHW date, max.DHW was used. If the survey occurs before the date of max.DHW, the DHW on the day before the survey occurred was adjusted to account for the remaining heat accumulation that occurred after the survey. The predicted 95% confidence intervals were estimated by bootstrapping 500 samples of 95% of the surveys per sample. Based upon this relationship, the total reef area exposed to accumulated heat stress that is likely to have experienced (a) no bleaching (b) minor to moderate bleaching and no mortality of living coral (c) major bleaching with low levels of mortality and (d) severe bleaching with high levels of mortality can be predicted.

The area of individual reefs was extracted from GBRMPA GBR features geospatial layer and survey sites were matched with individual reefs by proximity matches with 2km or less buffers around the sites, as not all the sites coordinates were inside the reef polygons. The DHW values for the sampling date and the maximum DHW were matched in the same way. A GIS project was set up using Quantum GIS software (QGIS, 2019, version 3.10.0)

All statistical analyses were performed using R language base package (R Core team, 2019, version 3.6.3) and tidyverse set of packages for data management and visualisation (Wickham, 2017).

3.0 RESULTS

3.1 Spatial trends in ocean temperature

Seasonal variation in temperature throughout the GBR establishes four distinct sectors of reef locations based on the annual temperature range across the length of the GBR ecosystem:

- Far North (9-14˚S; including the Torres Strait)
- Northern (14-18˚S; Innisfail to Cooktown)
- Central (18-21˚S; Mackay to Innisfail)
- Southern sector (21-24˚S; Mackay to Gladstone).

Winter minimum temperatures range from 18-22˚C in the southern sector to 23-25˚C in the Far North and are reached in August-September. Summer maximums generally occur in February and historically range from a maximum of 28˚C in the South to 29˚C in the Far North, with distinct regions of historically cooler upwelling regions at key offshore locations in the Far North and in the Swains and Capricorn Bunkers group in the South (Figure 4 and Appendix 1 Figure 1). Historical local summer maximum temperatures are the key factor in determining and predicting coral bleaching risk. Severity of the bleaching response following exposure to prolonged temperature anomalies above the historical maximum is determined by the combination of time and intensity of the summer peak temperature. Variation in the duration temperature anomalies (i.e. number of days above the MMM) and the absolute exceedance of the historical summer MMM between and within reefs and regions of the GBRMP will determine the ultimate severity of bleaching and potential for coral mortality due to thermal stress across the GBR ecosystem.

The summer of 2015 shows what a normal summer in the GBR looks like in terms of accumulated heat stress using the NOAA DHW product (Figure 4), with 0-2 DHWs throughout the GBR, which indicates summer maximum temperatures remained at or below the historical average MMM value throughout the entire length of the GBR. During the summer of 2016, the ocean heat wave in the Coral Sea and along the length of the GBR developed extreme accumulated thermal stress anomalies (i.e. Daily temperatures at least 1°C above the historic summer MMM) reaching maximum DHW values of 13.2 at reef locations (Figure 4), with prolonged temperature anomalies as high as 2.91˚C above the MMM. Thermal anomalies greater than the historical summer maximum (MMM) persisted throughout March, a time when summer temperatures usually begin to cool (Appendix 1 Figure 2). Heat stress exceeding five DHWs in 2016 developed throughout the Northern and Far Northern sectors of the GBR (Figure 4 and Appendix 1 Figures 3 and 6). Extreme anomalies and thermal stress DHW accumulation occurred again throughout the Far Northern GBR during the following year in 2017 for the first time in consecutive years, reaching maximum DHW values of 13.3, with the spatial footprint of extreme heat stress (DHW>8, max SSTA=3.22˚C) extending further south into the Northern and Central sectors of the GBR (Figure 4 and Appendix 1 Figures 3 and 7).

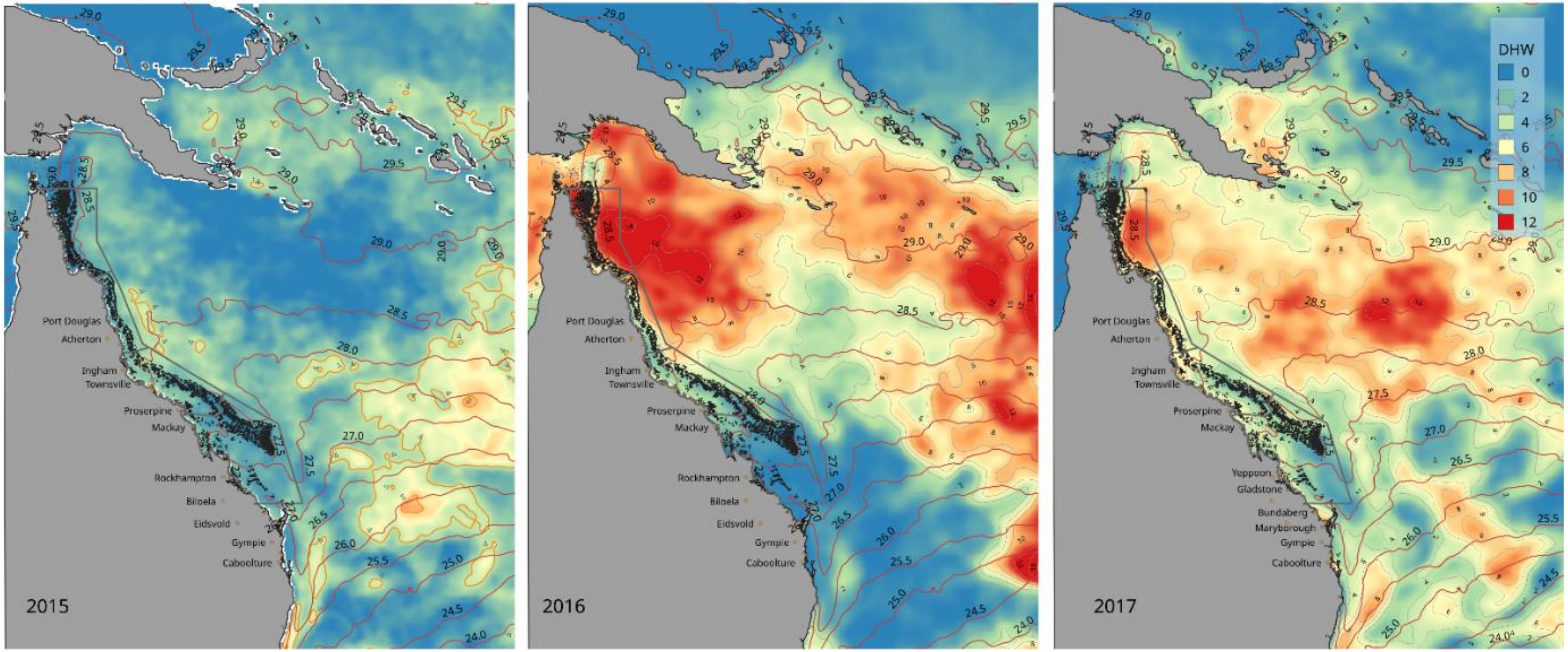


Figure 4: Accumulated heat stress measured by the NOAA Degree Heating Week (DHW) 5km satellite product (www.coralreefwatch.noaa.gov/satellite/bleaching5km/index.php; Daily Version 3.1) in 2015 (a normal summer), 2016 and 2017 along the Great Barrier Reef and the Coral Sea. This product combines the intensity of the daily temperature anomaly at least 1˚C above the historical summer maximum (MMM) temperature (upper thermal threshold) with the duration of time exceeding this threshold over a 12-week period. Previous bleaching events have shown that at DHW values from 0-4: no bleaching (ie. normal to just above average summer conditions), 4-8: possible bleaching, >8: extreme bleaching and widespread mortality likely.

Temperature anomalies (SST exceeding the MMM) and the spatial footprint of accumulated thermal stress (DHW>5) during the summer of 2016 and 2017 exposed more reef area to prolonged thermal stress than any previous year on record (Figure 5 and Appendix 1 Figure 3). To put the spatial footprint of the recent events in 2016 and 2017 into perspective, 0% of the GBR reef area accumulated a DHW>7.91 during the first documented mass bleaching event in 1998 (Figure 7). Conversely, 28.3% of the GBR was exposed to accumulated thermal stress levels of DHW>8 in 2016 and 27.1% in 2017. Maximum DHW values of 13.2 and 13.3 were accumulated in 2016 and 2017 respectively. The spatial footprint of severe temperature stress for 2016 and 2017 showed a 15.3-fold increase compared to the average area stressed in previous years (from 1990-2015) and 7.8-fold increase compared with previous heat waves that resulted in documented bleaching events in 1998, 2002 and 2006 (Berkelmans et al. 2004; Maynard et al. 2008) (Figure 5 and Appendix 1 Figure 3). Since reliable satellite SST monitoring records began in 1985, only 1987 resembles the total reef area exposed to heat stress like the recent 2016 and 2017 events. However, only 4.01% of the GBR reef area exceeded eight DHW in 1987, so this past temperature event was not as long and not as severe as 2016 and 2017 (Figure 5). Heat stress >8 DHW increases the likelihood of severe coral bleaching and mortality and indicates that ocean warming events are lasting longer and reaching new temperature extremes across bigger spatial areas throughout the GBR.

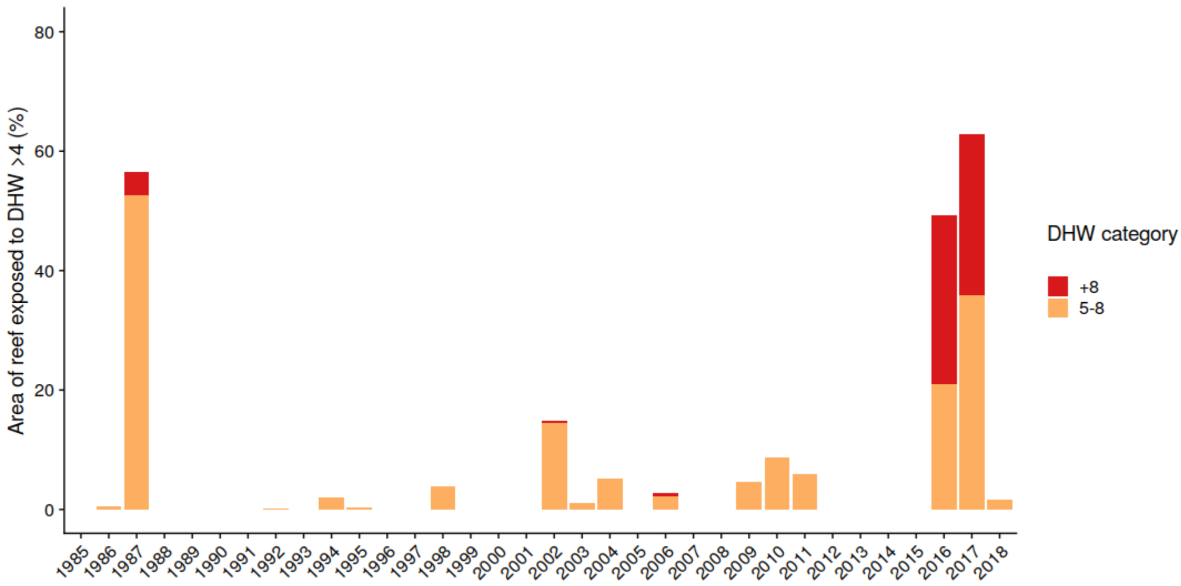


Figure 5: Total reef area exposed to severe accumulated heat stress (DHW>5) from 1992 to 2018. The heatwave events in 2016 and 2017 represents a 15.3-fold increase in relation to the average reef area exposed to major and severe DHW categories during this period and a 7.8-fold increase in reef area compared to previous known heat wave events that have caused documented coral bleaching on the GBR (1998, 2002, and 2006).

3.2 Spatial trends in coral bleaching severity and mortality

3.2.1 Combined aerial and in-water coral bleaching observations

With the increased spatial footprint of accumulated heat stress, the spatial distribution and total reef area with observed levels of major (Aerial Category 3: 30-60% community bleached) and severe coral bleaching (Aerial Category 4: >60% of the community bleached) has also increased in 2016 and 17 compared to the previously documented mass bleaching events on the GBR in 1998 and 2002 (Figure 6).

In 1998, 61.5% of the surveyed reefs were recorded as no bleaching (Aerial Category 0), with 19.2% of reefs confirmed to have major community level bleaching (Aerial Category 2 or 3) and only 1.6% of surveyed reefs severely bleached (Aerial Category 4; Appendix 1 Figure 4,). In 2002, 49.5% of the GBR reef area surveyed was confirmed not bleached with 28.2% major bleaching and only 0.7% severely bleached (Aerial Category 5 bleaching severity). Very little reef area was documented as severely bleached during these events. Results from the available surveys during the combined back-to-back bleaching events in 2016 and 2017 indicate that the spatial footprint of reefs not bleached was only 4.8%, while 39.6% of the total reef area of the GBR suffered major bleaching (Aerial Categories 2 and 3) and 35.0% recorded severe bleaching with mortality (Aerial Category 4) (Figure 6).

In 2016 most of the observations of severe community level bleaching occurred in the Northern and Far North sectors from Port Douglas into Torres Strait, with 44.7% of the total reef area surveyed scored as Aerial Category 4 throughout this northern third of the GBRMP (Figure 6 and Appendix 1 Figure 3 and 6). In 2017, the spatial footprint of severe community level bleaching (Aerial Category 4) extended further south, into the central sector of the GBR, expanding the severely bleached area of the GBR, with 33% of the surveyed reef area between Townsville and Cooktown scored as Aerial Category 4 (Figure 8 and Appendix 1 Figure 7). The reefs surveyed represent 57% of the total designated reef area throughout the GBRMP. By the end of the consecutive back-to-back bleaching events in 2016 and 2017, 74% of the GBR total reef area surveyed suffered major and severe bleaching with 35% of the surveyed reef area documented as severely bleached (>60% of the community) at least once over the two years.

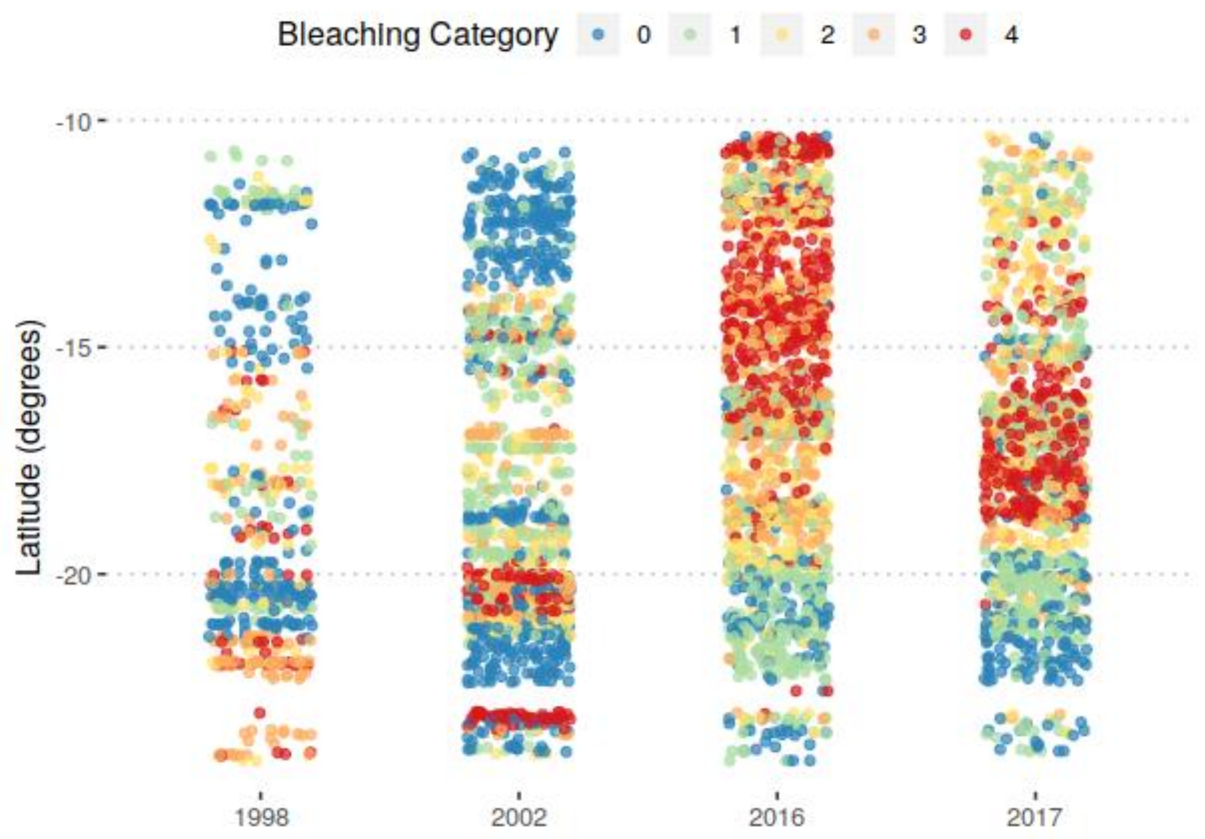


Figure 6: Spatial variability of documented bleaching observations and bleaching severity along the entire length of the Great Barrier Reef in 1998, 2002, 2016 and 2017. Datasets include both aerial observations (Berkelmans 1998 and 2002, Hughes et al. 2016 and 2017) and in-water observations (RHIS and Transect based methods). Community level bleaching categories is based on the total percentage of both hard and soft corals combined visibly bleached: Category 0=<1% no bleaching, Category 1=1-10% minor bleaching, Category 2 = 10-30% moderate bleaching, Category 3=30-60% major bleaching, Category 4=>60% severe bleaching.

3.2.2 In-water coral bleaching severity and mortality observations

Coral bleaching responses at the community level increased on average by 20% at DHW values between 5-8 DHW and by 45% at DHW> 8 (Figure 9) compared to reefs below 4 DHW (Figure 9). Community mortality increases on average by 11.5% (range between 1-22% in 95% of the surveys) when the accumulated heat stress exceeds 8 DHW (Figure 10B). At DHW 0-2, coral community bleaching was low (12.8% bleached). Coral bleaching increased to 28.5% at reefs exposed to a DHW 2-4. Reefs exposed to a DHW5-8 were 33.7% bleached in 2016 and 58.0% bleached in 2017 while reefs at extreme heat stress at DHW>8 were 76.8% bleached in 2016 and 69.5% bleached in 2017 (all values reported are median % bleaching; Figure 9). Some reef surveys documented up to 99% of the reef community bleached at both DHW5-8 and DHW>8.

In-water surveys provide an essential assessment of the bleaching severity observed for individual coral colonies within the community, from minor bleaching with recovery potential (Bleaching State 3) to severe bleaching and direct mortality (Figure 5). Both the quantitative transect based methods and qualitative RHIS based observations reveal a significant increasing trend in the proportion of coral bleaching with increased heat stress accumulation

(Figure 7). Qualitative RHIS based visual estimates contribute considerably more variation in bleaching estimates across all DHW stress categories (Figure 7). Low estimates of community bleaching within the RHIS based datasets were observed at reef sites exposed to severe DHW stress >5 DHW was related to the timing of surveys. These low estimates of bleaching could have occurred because the surveys were conducted either too early in the warming event, >30 days before peak heat stress, or too late after peak heat stress (>40 days after) DHW accumulation ended (Figure 7). At severe levels of heat stress (DHW >8), severe mortality is expected to occur within 1-2 weeks of peak heat and surveys conducted 4-6 weeks later could underestimate coral bleaching prevalence as recently dead coral colonies quickly become overgrown with algae.

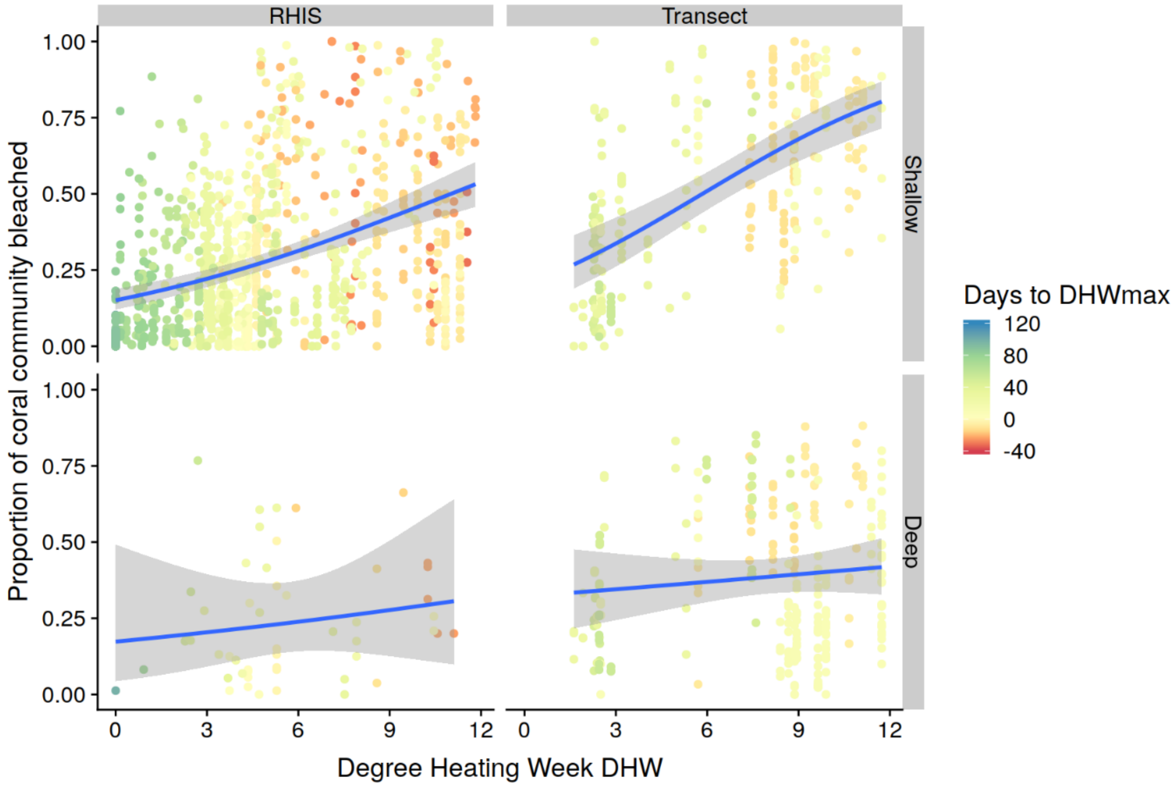
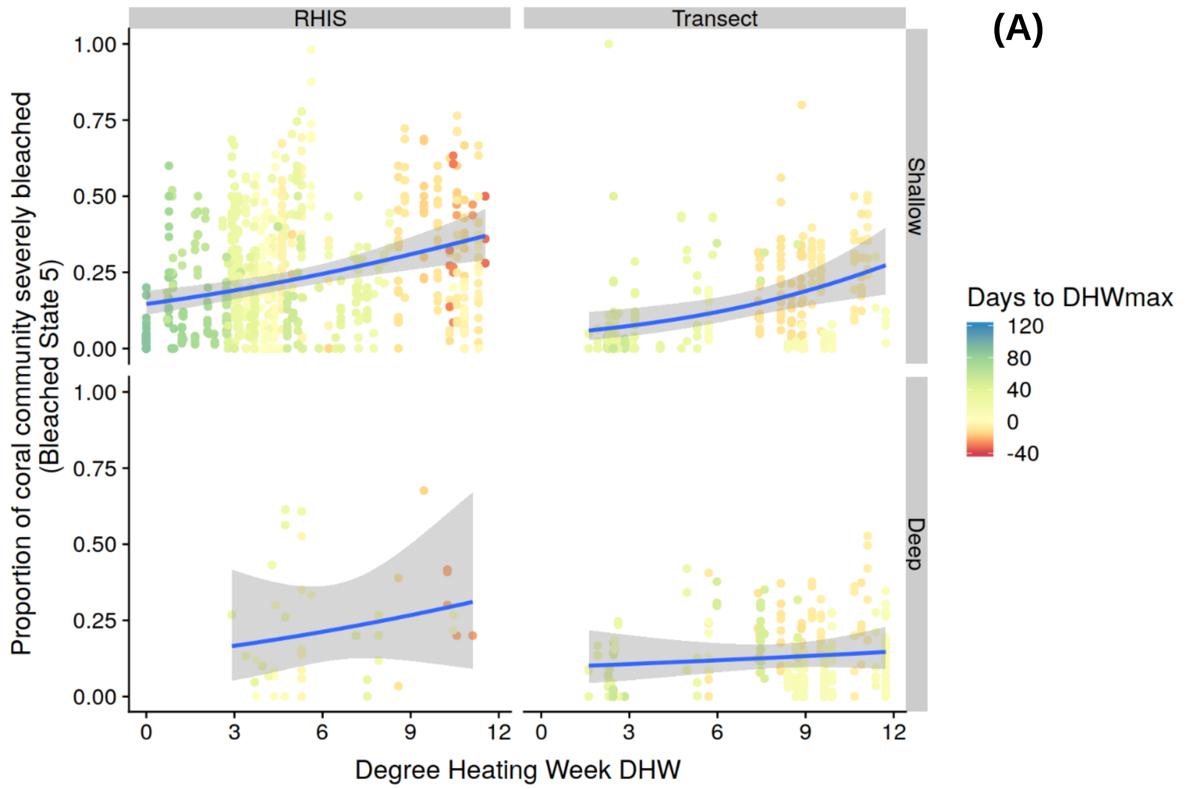


Figure 7: In-water proportion of coral bleaching (% of hard and soft corals >5cm in diameter of the coral reef community) in relation to the reef maximum annual DHW accumulation for 2016 and 2017 combined, quantified from qualitative RHIS estimates (left 2 panels) and transect based methods (right two panels). Depth of survey (i) shallow (0-6m) and (ii) deep (7-40m). Each observation is colour coded in relation to how the date of the survey relates to the date at which Maximum DHW accumulation occurred (0 DHW.daystomax), which represents the end of heat stress.



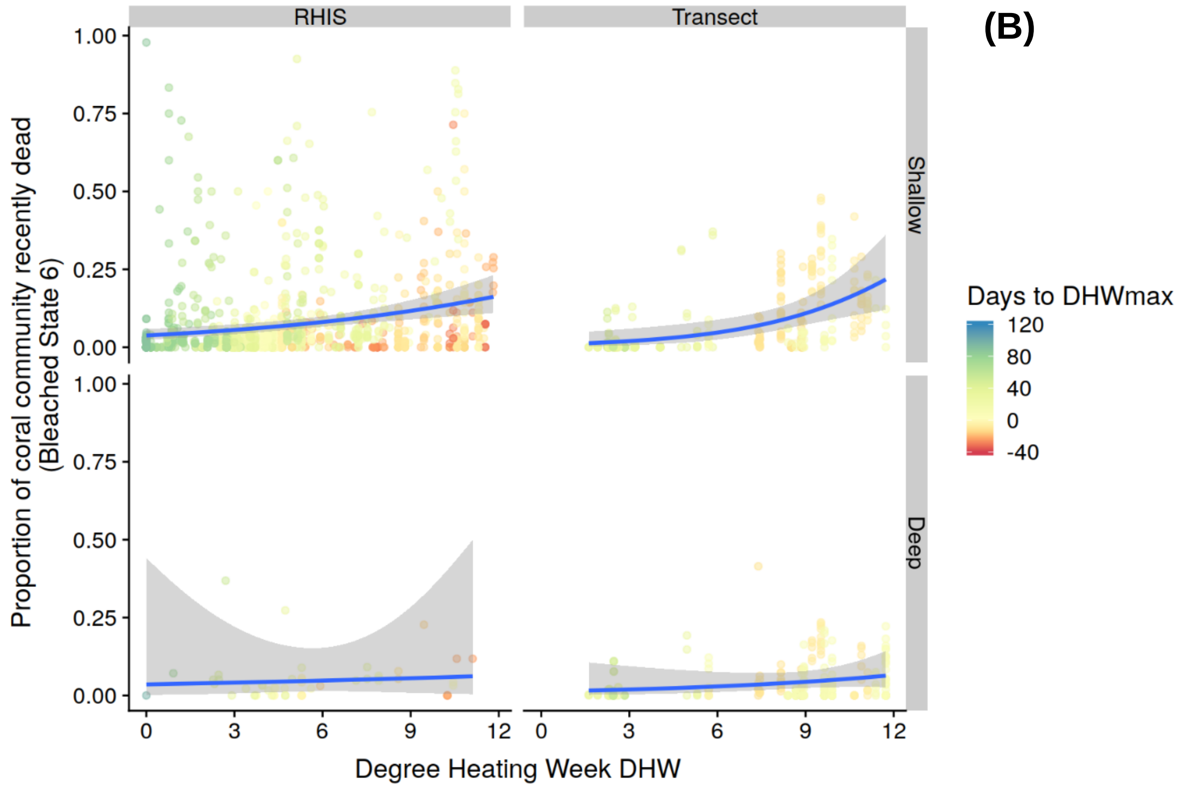


Figure 8: (A) Proportion of the coral reef community that were severely bleached (Bleached State 5) completely white with or without fluorescent pigments. (B) Proportion of the coral reef community that was recorded as recently dead due to heat stress and bleaching (Bleached State 6) at the time of the surveys conducted at or near the peak of heat stress during the summer. Depth of survey (i) shallow (0-6m) and (ii) deep (7-40m). Each observation is colour coded in relation to how the date of the survey relates to the date at which Maximum DHW accumulation occurred (0 DHW.daystomax), which represents the end of heat stress.

In-water bleaching observations of severely bleached corals, completely white with or without fluorescence indicates a complete loss of algal symbiont. Severe bleaching becomes more prevalent at DHW accumulation levels above 5 (Figure 8A and 9). Only 4.9% of the corals were scored as severely bleached (Bleaching State 5) at DHW<2. As the intensity and duration of warming increases, the proportion of severely bleached corals increases to 15.3% at DHW5-8 and 22.9% at DHW>8 (median response). Maximum observations of severely bleached corals reached 40.6 and 80% at DHW 5-8 and >8 respectively (Figure 8A).

Coral mortality due to thermal stress ranged from 1.9-97.8% from all in-water surveys during the 2016 and 2017 summers. Coral mortality at the reef population level across the GBR from all in-water surveys (median response) was 3.2% at a DHW2-4; 6.9% in 2016 and 6.6% in 2017 at a DHW 5-8; and 14.5% in 2016 and 15.8% in 2017 at a DHW>8 (Figure 8B). Including the proportion of the reef corals recorded as severely bleached and the recently dead colonies combined at the peak of heat stress (Bleaching State 5 + 6), 33.1% (DHW 5-8) and 15.9% (DHW>8) in 2016, and 29.9% (DHW 5-8) and 50.0% (DHW>8) in 2017, of the reef community is at risk of mortality during the recovery period in the months following maximum peak heat stress (Figure 9) when exposed to the more severe DHW categories.

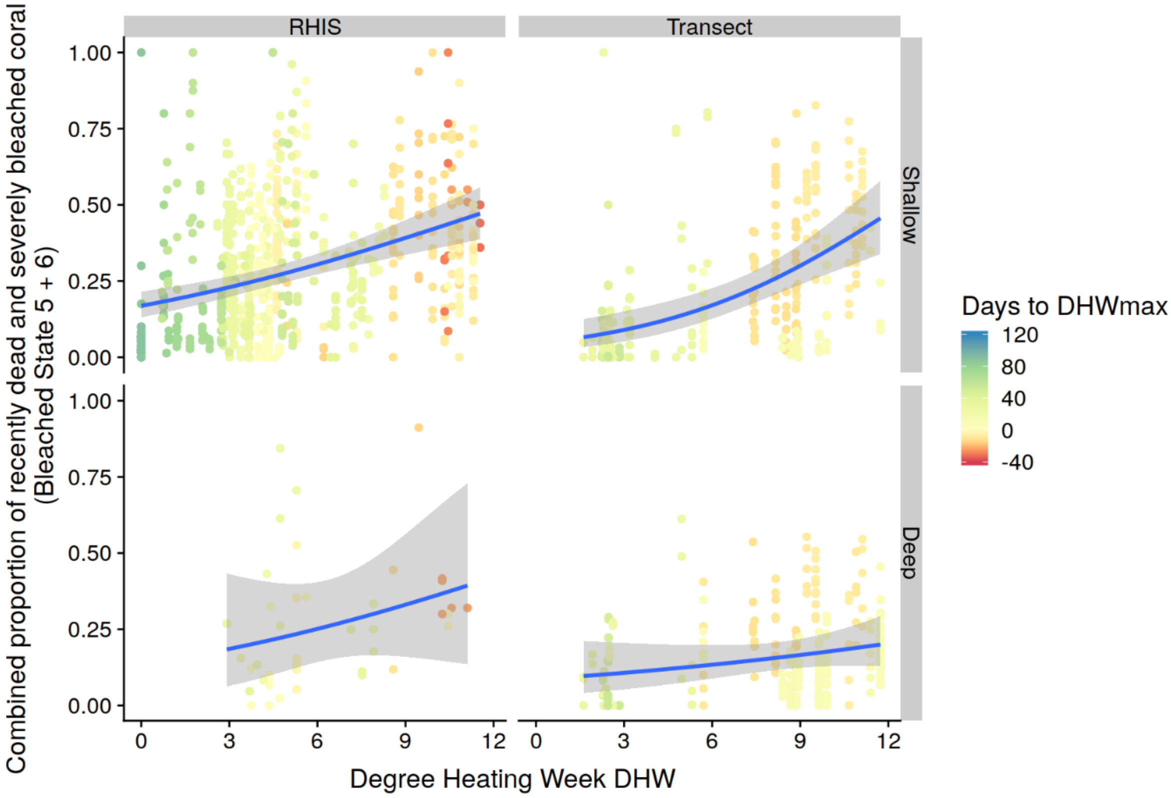


Figure 9: Combined proportion (%) of the reef community that were severely bleached (Bleached State 5) and recently dead (Bleached State 6). Severely bleached corals are at risk of mortality after the date of survey adding to the potential impact from the bleaching response. Depth of survey (i) shallow (0-6m) and (ii) deep (7-40m). Each observation is colour coded in relation to how the date of the survey relates to the date at which Maximum DHW accumulation occurred (0 DHW.daystomax), which represents the end of heat stress.

3.3 Spatial area of coral reef impacted by accumulated heat stress

Using the spatial coverage of the satellite SST monitoring products (NOAA DHW v3.1), the total area of reef that was exposed to various defined categories of heat stress was quantified. The expected severity of coral bleaching across the DHW range from 2016 and 2017 is defined as: (1) minimal bleaching at DHW 0-2; (2) corals bleached at DHW 2-4 (3) major bleaching and some mortality at DHW 5-8 and (4) severe bleaching (completely white corals) and extensive coral mortality at DHW >8. This relationship is based on the observed level of bleaching severity and maximum DHW exposure (Figures 7, 8 and 9). It is the higher categories of accumulated heat stress (DHW>5) that will cause shifts in community species composition and loss of living coral cover due to coral mortality induced by thermal stress in a warming ocean.

In 2016, 64.5% of the total reef area of the GBR reached an accumulated level of heat stress (DHW>2), that can cause bleaching. The total area of the GBR that reached major levels of heat stress was 20.9% DHW 5-8 range, that will cause major bleaching and some mortality and 28.3% of the GBR reef area was exposed to a DHW >8 that will cause severe bleaching and mortality (Figure 10). In 2017, 90.6% of the total reef area of the GBR reached an accumulated level of heat stress (DHW>2), that can cause bleaching, with 35.8% of the reef area exposed to DHW 5-8 and 27.1% of the reef area exposed to DHW >8 (Figure 11). During the back-to-back bleaching event in 2016 and 2017, the combined total reef area exposed to extreme accumulated heat stress (DHW>5) at least once in the two years was 66.9% (Figure 10 and 11). Only 3.9% and 14.9% of the reef area of the GBR was exposed to this level of heat stress in 1998 and 2002 respectively (Appendix 1 Figure 1 and Appendix 1 Figure 2).

At reefs without survey observations a binomial generalized linear model to predict the average bleaching response was developed: (i) % bleached and (ii) % severely bleached and recently dead (Bleached State 5+6) at the level of heat stress accumulated throughout the entire GBR reef area in 2016 and 2017 (Figure 12 and Table 1 and 2). Predicted levels of coral bleaching remain low (19-33.9%) at DHW heat stress levels between 0-4 DHW’s. Coral bleaching progressively increases to an average predicted bleaching proportion of 51% at DHW 5-8 and 72% at reefs exposed to DHW > 8 (Figure 12A and Table 1). On average the proportion of the reef community that is likely to be severely bleached and or dead after peak heat stress is less than 10% at DHW heat stress levels between 0-4 (Figure 12B and Table 2). Levels of severe bleaching and mortality increase to 17-22% of the community at 5-8 DHW’s and 35-45% of the community at any given reef that exceeds 8 DHW’s (Figure 12b and Table 2). The total reef area of the GBR exposed to this level of heat stress during both the 2016 and 2017 heat waves, exceeded 50% in both years with an expanding southward trend of heat stress in the second bleaching year of 2017 (Table 1 and 2).

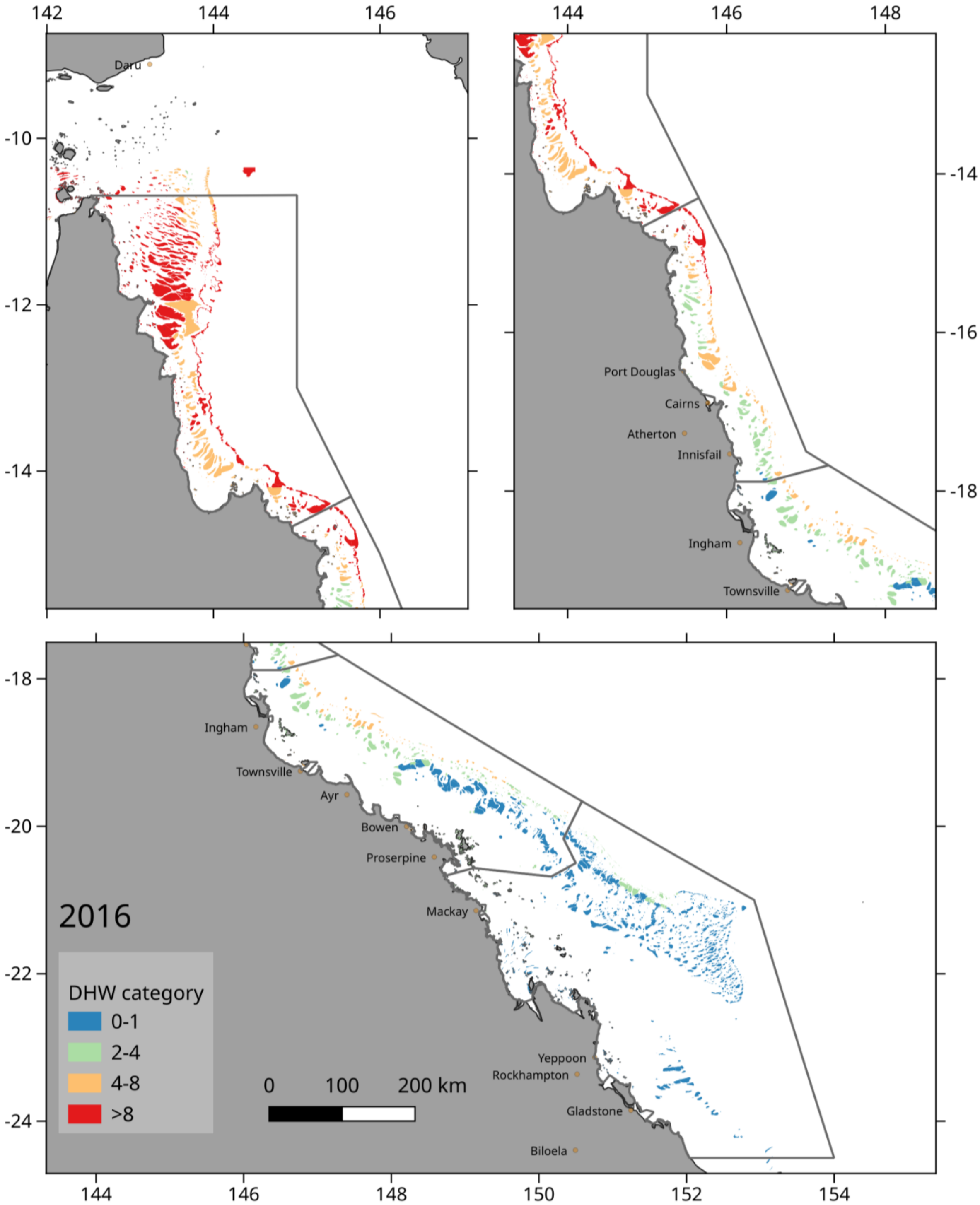


Figure 10: Maximum Degree Heating Week in 2016 using GBRMPA spatial layer. Based on recent bleaching observations reefs exposed to DHW 2-4 are at risk of minor-moderate bleaching, DHW 5-8 major bleaching and some mortality and DHW>8 severe bleaching and mortality.

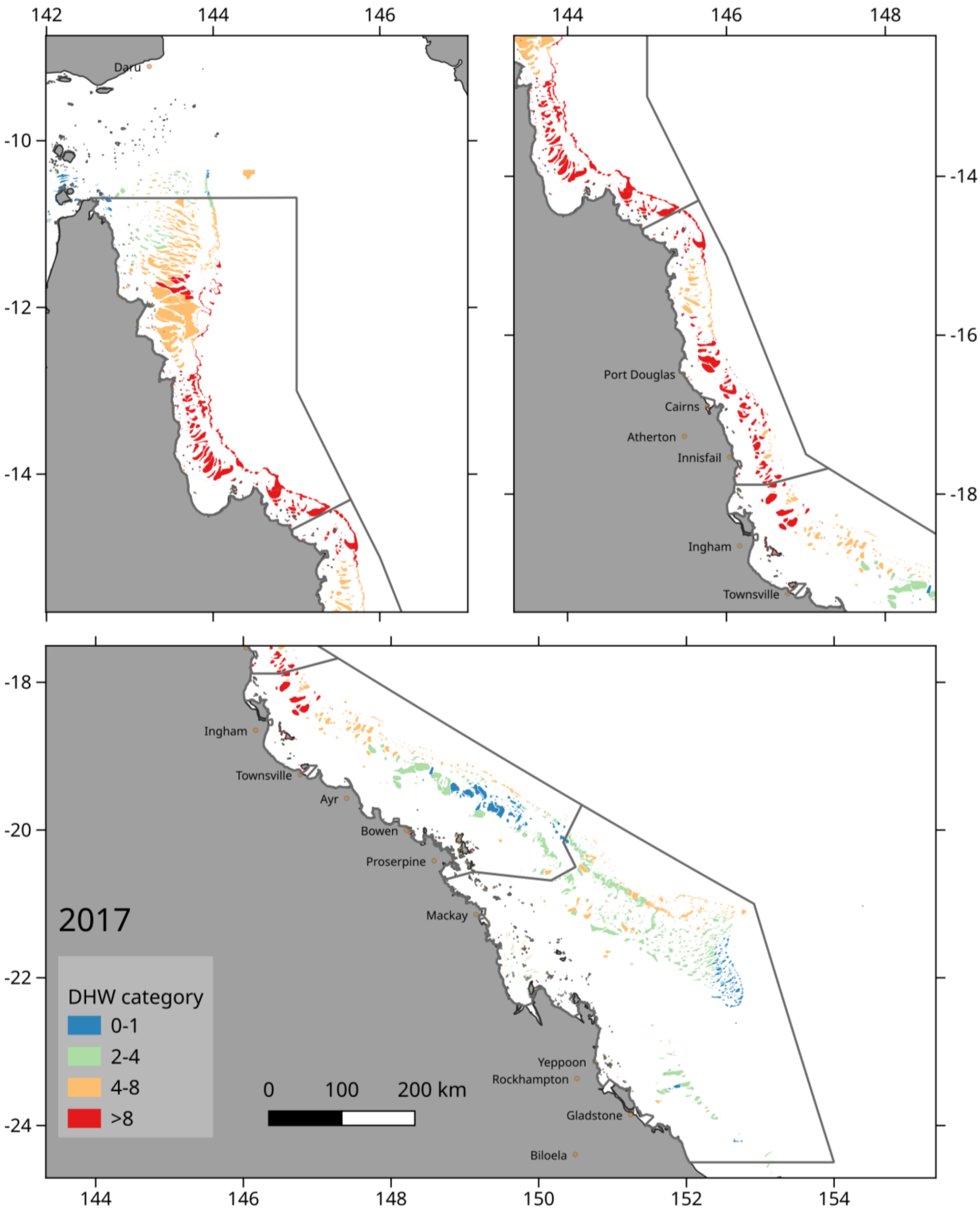


Figure 11: Maximum Degree Heating Week in 2017 using GBRMPA spatial layer. Based on recent bleaching observations reefs exposed to DHW 2-4 are at risk of minor-moderate bleaching, DHW 5-8 major bleaching and some mortality and DHW>8 severe bleaching and mortality.

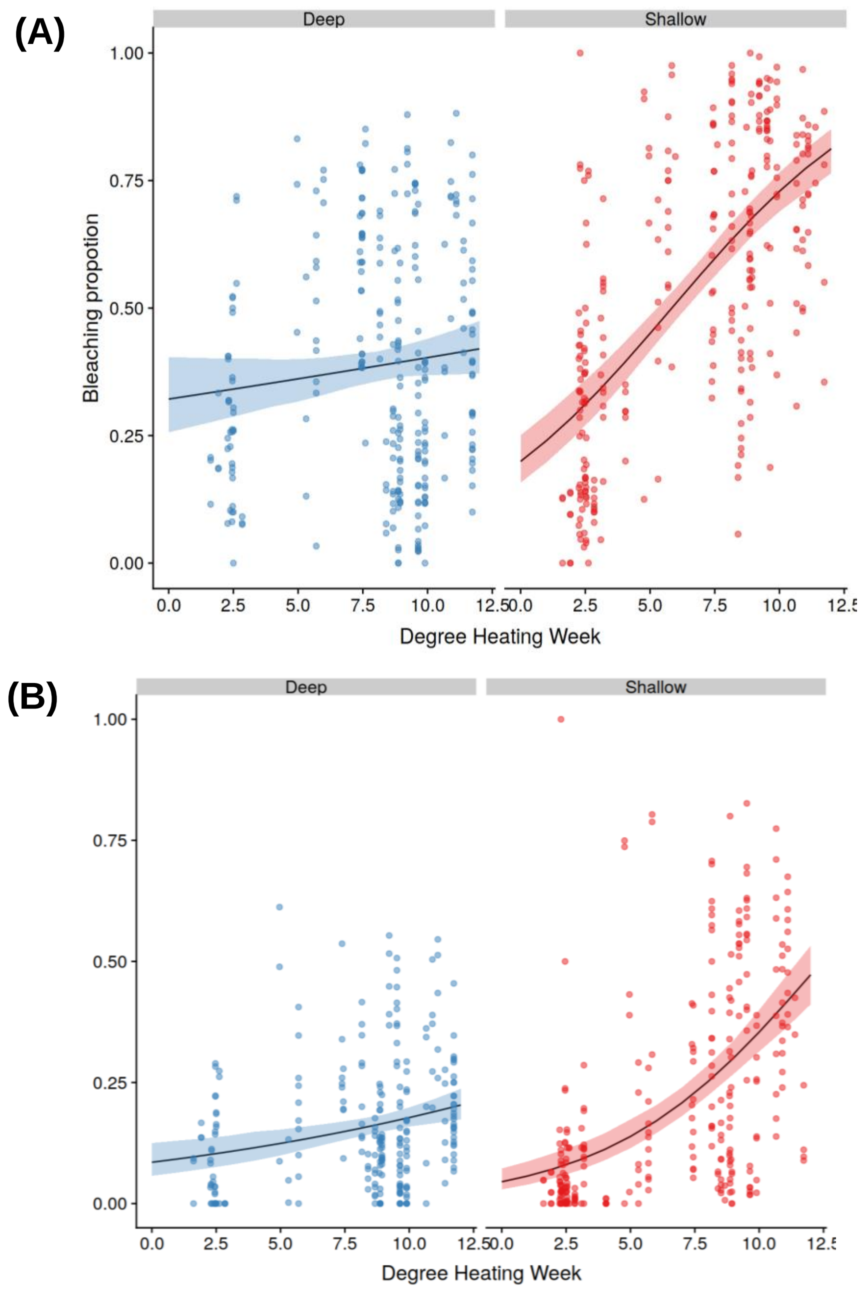


Figure 12: Coral bleaching and corals at risk of mortality at a given accumulated level of heat stress. Regression curves fitted using binomial generalized linear models, with 95% confidence limits. (A) Proportion of hard and soft coral community bleached. (B) Combined proportion (%) of the reef community that were severely bleached (Bleached State 5) and recently dead (Bleached State 6). Severely bleached corals are at risk of mortality after the date of survey adding to the potential impact from the bleaching response. Depth (i) shallow (0-6m) and (ii) deep (7-40m).

Table 1: Quantified total reef area of the GBR (km^2 and %) and the predicted level of reef community bleaching severity (% bleached of hard and soft corals) at all GBR reef locations from the binomial generalized linear model for 2016 and 2017.

DHW category	Year	Reef area (km^2)	Reef area (%)	Area bleached (km^2)	Predicted level of Community Bleaching (%)	CI 95%-lower	CI 95%-upper
0	**2016**	900.60	3.21	179.59	19.94	11.03	28.85
	2017	--	--	--	--	--	--
1-2	**2016**	7658.80	27.26	1844.11	24.08	15.20	32.95
	2017	3116.06	11.09	794.77	25.51	16.66	34.35
3-4	**2016**	4820.76	17.16	1580.49	32.79	24.59	40.98
	2017	8870.58	31.57	3014.03	33.98	16.66	34.35
5-8	**2016**	6390.58	22.74	3282.37	51.36	44.84	57.89
	2017	9267.77	32.98	4667.58	50.36	43.86	56.86
+8	**2016**	8260.64	29.40	5930.75	71.80	64.63	78.96
	2017	6776.99	24.12	4914.90	72.52	65.30	79.75

Table 2: Quantified total reef area of the GBR (km^2 and %) and the predicted level of severely bleached and recently dead coral colonies within the community (% bleached of hard and soft corals) at all GBR reef locations from the binomial generalized linear model for 2016 and 2017.

DHW category	Year	Reef area exposed (km^2)	Reef area exposed (%)	Area bleached (km^2)	Predicted level of severe bleaching and mortality (%)	CI 95%-lower	CI 95%-upper
0	**2016**	900.60	3.21	40.58	4.51	0.77	8.24
	2017	--	--	--	--	--	--
1-2	**2016**	7658.80	27.26	438.71	5.73	1.59	9.86
	2017	3116.06	11.09	191.89	6.16	1.90	10.42
3-4	**2016**	4820.76	17.16	417.31	8.66	3.93	13.38
	2017	8870.58	31.57	808.11	9.11	4.34	13.89
5-8	**2016**	6390.58	22.74	1138.25	17.81	12.71	22.91
	2017	9267.77	32.98	1586.06	17.11	12.05	22.18
+8	**2016**	8260.64	29.40	2887.50	34.95	26.53	43.38
	2017	6776.99	24.12	2427.97	35.83	27.09	44.56

3.4 Bleaching severity at depth

From the available bleaching observations, the majority of in-water observations include shallow water reef habitats above 6m (Appendix 1 Figure 10). However, observations made at offshore locations along the reef slope to depths of 25 - 40m (Baird et al. 2018; Frade et al. 2018) and in mid-range exposed reef slope locations (7-10m) align with AIMS long-term monitoring sites and depths. Coral bleaching was not restricted to shallow reef environments during the 2016 and 2017 bleaching events on the GBR, however across all DHW heat stress levels, bleaching severity was reduced at depths >7m (Figure 7, 8 and 9). Coral bleaching severity in deep reef environments ranged from 20-90% in 2016 and from 25-75% of the coral community in 2017 (Figure 7). On average, deep reef habitats from transect based methods exhibit an average reduction in the proportion of the coral community bleached by 32.5% (2016) and by 9.2 % (2017) at a DHW>8 and by 14.8% in 2017 at a DHW 5-8, compared to shallow reef habitats at the same level of heat stress (Figure 7, 9 and Table 3).

Table 3: Effect of the depth on bleaching severity by depth at DHW>5. Data is from 2016 and 2017 using quantitative transect based survey observations only. Bleaching indicators include % severely bleached colonies (Bleaching State 5), combined % of severely bleached and recently dead colonies (Bleaching State 5+6), % recently dead (Mortality; Bleaching State 6) and % community bleached. The values are the coefficients of the depth variable (size of the effect) and its 95% confidence interval. The coefficients could be interpreted as the change in the percent of bleaching due to change from shallow to deep water areas, with negative coefficients indicating reduced response with increasing depth. NS: No significant differences.

Bleaching indicator	Year	DHW 5-8	DHW >8
Severely Bleached Bleaching State 5	2016	NS	
	2017	NS	
Combined Bleaching State (5+6)	2016	NS	
	2017	-1.587 (-6.816, 3.642)	
Mortality	2016	-2.064 (-9.028, 4.874)	
	2017	-1.587 (-6.816, 3.642)	
Community Bleached	2016	NS	-32.459 (-40.183, -24.735)
	2017	-14.840 (-23.961, -5.719)	-9.241 (-16.085, -2.397)

3.5 Within reef observations and variability

During the summer heat wave and bleaching events in 2016 and 2017, most of the available data represents one survey score per reef, dominantly from the aerial survey method, which is vital to capturing a full assessment of the spatial severity of coral bleaching. More than 100 reefs have five or more survey estimates of bleaching severity in both 2016 and 2017 (Table 4). However, in order to control for the possible effects of the duration and severity of heat stress at a given reef, the analysis was restricted to only include reefs with at least five surveys that occur within 21 days of the date at which the Maximum DHW value was reached. This reduces the number of reefs available for assessment of within reef variability to 25 (2016) and 14 (2017) and only includes RHIS based observations. Reefs with multiple surveys (≥ 5) were located between 11.8-18.85°S in 2016 and between 16.11-16.93°S in 2017. With the available data, RHIS based bleaching estimates produce high variability, particularly at the major and severe heat stress categories. This variability also indicates a contradictory reduction in bleaching severity at reefs exposed to DHW >8 in 2017 (Figure 13).

Table 4: Total number of surveys in 2016 and 2017 as an indication of the total number of observations within a single including all data available (Aerial, RHIS, and Transect based methods.

Survey Year	Surveys within an individual reef	Total number of Reefs by survey
2016	1	799
	2-5	72
	5-10	31
	10+	86
2017	1	630
	2-5	58
	5-10	42
	10+	63

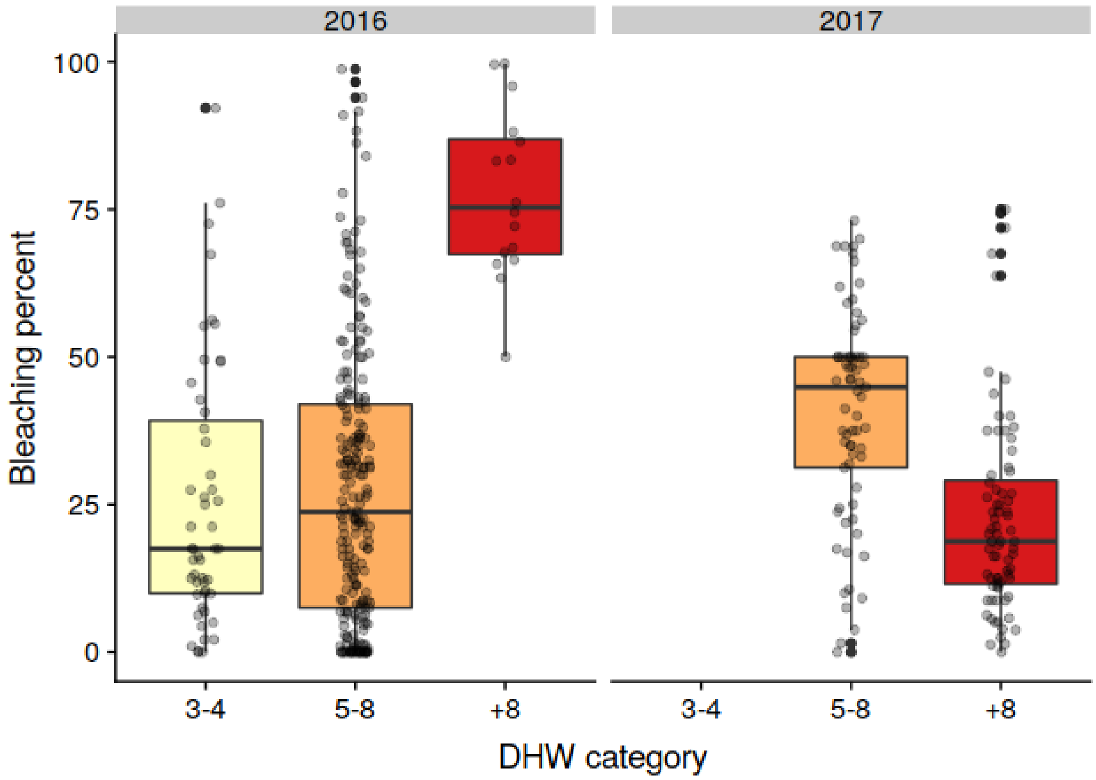


Figure 13: Assessment of within reef variability at the same level of heat exposure. RHIS estimates of bleaching response (% of coral community) conducted at reefs with >5 RHIS surveys within the same reef location and within ± 21 days of peak heat stress (Maximum DHW accumulation) to control for temperature exposure. Observations split by year (2016 and 2017) and categorised by DHW severity 3-4 (n reefs=8), 5-8 (n reefs = 21) and >8 (n reefs =10).

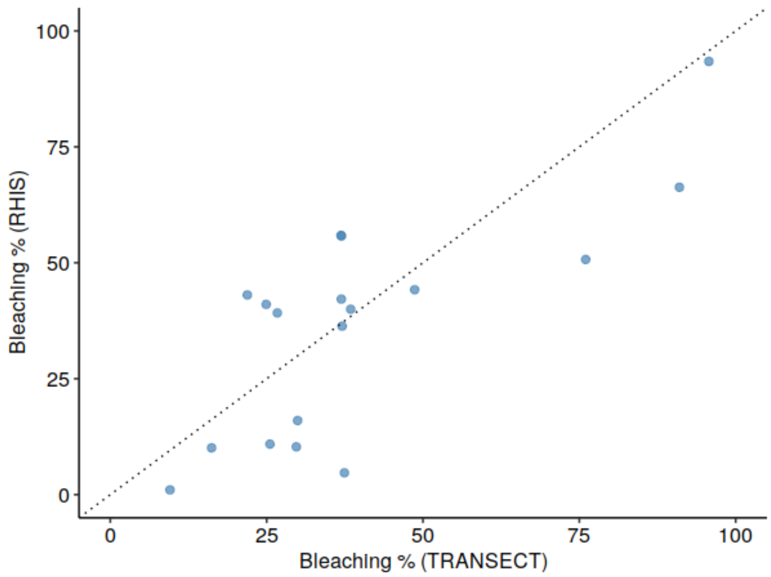


Figure 14: Direct comparison of bleaching estimates (% bleached) from Reef Health and Impact Surveys and AIMS quantitative transect based methods conducted at the same reef on the same day in 2016 throughout the central GBR between Townsville and Port Douglas.

At a selected number of reefs during the 2016 bleaching event a set of RHIS and transect based bleaching severity estimates provided multiple observations within the same reef and habitat to directly compare the consistency of the survey approach at the same level of DHW heat stress. There was no significant difference in the median level community bleaching estimate, when reef site and heat stress exposure level is carefully controlled (Figure 14; Wilcoxon paired V = 105, p-value = 0.417).

4.0 DISCUSSION

4.1 Spatial impacts of coral bleaching and mortality

The ocean warming event in 2016 and 2017 has been the most prolonged, thermal stress event to develop across the widest spatial reef area of the GBR in recorded history. Following the 1998 bleaching event on the GBR based on global circulation model simulations it was predicted that warming events as severe as the 1998 event would be commonplace within 20 years (Hoegh-Guldberg 1999). These scientific predictions have been exceeded by the current observed rate of ocean warming. Results based on both the satellite remote sensing of ocean temperatures throughout the GBR and survey observations of coral bleaching and mortality clearly indicate that during the 2016 - 2017 two-year bleaching event on the GBR, 6.7 times more reef area was exposed to extreme accumulated levels of heat stress (DHW>5; Figure 5, 6) than any of the previously recorded bleaching events on the GBR (1998, 2002 and 2006 (Berkelmans et al. 2004; Maynard et al. 2008; Hughes et al. 2017; Hughes et al. 2019).

Observed levels of coral community bleaching (% of the living corals) have also increased compared to any other documented bleaching events. By the end of the back-to-back bleaching event, only 4.8% of the surveyed reef area was documented as not bleached (0% of living coral showing signs of thermal stress), mostly restricted to the southern third of the GBR and 39.6% of the surveyed reef area was scored as major bleaching (10-60% of the living coral bleached) and 35.0% of the surveyed reef area was recorded as severely bleached (>60% of the living coral bleached) with recently dead corals. Only 1.6% and 0.7% of surveyed reef locations in 1998 and 2002 were recorded in this severely bleached category. Based on current climate model predictions, future warming events of this scale or worse are likely to occur more frequently in the next decade (Donner et al. 2005; Heron et al. 2017). This event is only the beginning of more frequent heat waves and severe coral bleaching for the GBR as ocean warming trends continue.

Bleaching related coral mortality by the end of summer peak heat stress (May) used in this study indicates that the expected levels of coral mortality due to direct thermal stress driven oxidative stress, across the GBR as a whole was 11-15% loss of living coral at the reefs exposed to DHW>5 (66.9% of the GBR reef area), with maximum observations of mortality as high as 97.8% at some reefs. Given the proportion of severely bleached (100% white; Category 5 Figure 5D, 13, 18) living corals at the time of these surveys, there is the potential and likelihood of increased mortality by 12-50% (Figure 9). During the months following the thermal stress anomalies, severely bleached corals are at an increased risk of death due to either starvation if the symbiont recovery processes fail, or through infectious diseases which exacerbate mortality following a bleaching event (Brodnicke et al. 2019). Time-series studies on the GBR with frequent observations during the entire bleaching and recovery phases of the event, indicate that severely bleached branching and tabular *Acropora spp. a*re particularly at risk of either whole colony mortality or partial mortality. Only 12% of severely bleached *Acropora hyacinthus* tables survived the 1998 bleaching event (Baird & Marshall 2002) and 0% of the tagged colonies that were severely bleached at Beaver Reef in March 2017 (55 of 100 tagged colonies were severely bleached at the time of peak heat stress) survived past June (4 months after peak heat stress) (Brodnicke et al. 2019). Other growth forms and species have displayed higher survival patterns following severe bleaching with survivorship rates ranging from 8-75% depending on the species and growth form (Baird and Marshall 2002; Jones 2008). However, all of these detailed time-series studies indicate that the majority of whole colony mortality or partial mortality of severely bleached corals occurs within the first month to 3-4 months after peak heat stress (Baird and Marshall 2002; Jones 2008; Brodnicke et al. 2019). Longer term loss of living coral cover following the 2016 bleaching event was documented in the northern GBR, with declines in cover increasing with extreme levels of heat stress above 4 and 8 DHW's (Hughes et al. 2018). Rates of coral mortality documented as a loss of coral cover in November 2016 (Hughes et al. 2018) closely resemble the predicted potential mortality of the severely bleached individuals at the peak of the heat stress event (Bleached State 5+6; Figure 9). The proportion of the reef community at risk of mortality due to severe coral bleaching is a reliable metric of severity and impact of thermal stress events impacting upon the survivorship of stressed individuals within the community.

Since thermal bleaching is driven by the combination of high levels of solar radiation, ultra violet (UV) radiation and warm temperature anomalies above the normal thermal range of the reef and or habitat (Lesser 1997; Jones et al. 1998; Jones 2008), it is expected that deeper reef habitats could provide refuge against increased patterns of coral bleaching in a warming ocean. Quantitative observations of bleaching severity and mortality below 10m remain very limited across the GBR, mainly due to the prioritization of available vessel time and field teams to assess the spatial impacts across as many locations throughout the ecosystem as possible. Diving regulations in Australia also make it challenging to conduct scientific observations at depths >20-30m, within the no-decompression limits of the DCIEM tables. Growing evidence indicates that bleaching severity declines at depths >6-10m (Bridge et al. 2013; Muir et al. 2017; Baird et al. 2018; Frade et al. 2018). From the available data at depths >6m along the length of the GBR there was an observed reduction in the community level bleaching response by 9-32%.

Mortality due to bleaching in the northern sectors of the GBR at 40m was half the level of mortality (5.7%) observed at shallower depths of 5, 10 and 25m (11.8%, 8.4% and 10.5%) (Frade et al. 2018) and three times lower than the 75th percentile of mortality quantified for all reefs exposed to a DHW>8 at depths <6m across the entire GBR in this study. However, significant shifts in the community composition have been documented along these depth gradients which also influences the risk of bleaching and the ultimate severity of bleaching at depth, as growth forms, taxa and species that are more resistant to bleaching are more abundant at depth (Muir et al. 2017; Baird et al. 2018; Frade et al. 2018). Most observations have not been made to species level, which also makes it challenging to confirm if reductions in bleaching severity are caused directly by depth or if it is related to shifts in species abundance within genera across wide depth gradient that drives bleaching susceptibility. However, in the Maldives, when species are documented across wide depth ranges (3-11m vs 24-30m) the majority of species (97% of 136 species) display reduced bleaching response with depth (Muir et al. 2017). Warming patterns throughout the depth range in 2016 indicate that although temperatures do not reach the same maximum value as the shallow reef, compared to the normal summer maximums at depth, anomalies reached 1.5 and 1.8˚C above the previous summer maximums at 10 and 40m respectively (Frade et al. 2018). With the development and advances in technology, the use of autonomous underwater vehicles will become more widely available during bleaching response survey efforts in the future to expand the coverage of quantitative assessments of coral bleaching across greater depths. Despite both shifts in species composition and significant warming at depth during the recent event, deep water communities across most coral taxa reveal reduced severity in coral bleaching and mortality.

4.2 Ecological dynamics and coral bleaching on the GBR

Variability exists in the overall levels of observed bleaching and mortality across and within each category of accumulated heat stress (DHW), even at extreme levels of DHW>8 despite strong, consistent overall increases in bleaching and mortality at DHW>5. This variability is likely attributed to undetected hydrodynamic mixing (wind, currents and tidal driven mixing) influencing the warming rate within a reef that is not fully captured at the 5km pixel resolution of the satellite SST products, biological factors that drive variability in tolerance and ecological factors related to community composition of reefs within and between heat stress (DHW) categories. Incorporating aspects of coral cover, species richness within the community and the bleaching susceptibility of the most abundant coral species within the coral community has strong influences on the severity of the bleaching response at a given heat exposure and can explain the observed variability. Heron et al. (2016) showed that coral cover and generic richness of the community increases the predictive capacity of the NOAA SST heat stress products (DHW). If a reef is dominated by tolerant coral species, at an equivalent DHW stress level (ie. DHW5-8 or >8), the bleaching severity and subsequent mortality will not be as high as a reef that is dominated by sensitive coral species (eg. Acropora plating species (Baird and Marshall 2002; Hughes et al. 2017). Likewise, as bleaching events impact reef areas repeatedly in back-to-back years and become more frequent into the future, the ecological impacts from the first year will shift the community bleaching response in the second year at the same level of heat stress (Hughes et al. 2019). As the spatial footprint of severe heat stress (DHW>5) increases, the documented spectrum of bleaching tolerance across coral taxa (Baird & Marshall 2002) has considerably changed, with previously documented tolerant coral species and taxa bleaching more frequently at higher levels of heat stress (Hughes et al. 2017). Community composition across wider reefs will shift from fast growing bleaching sensitive species, to the fewer remaining tolerant coral taxa following the 2016 and 2017 bleaching events (Hughes et al. 2017), which could shift the documented response relationship between DHWs and bleaching severity as marine heat waves occur more frequently (Hughes et al. 2019). During the 2016 - 2017 event, overall 45% of the total GBR reef area was exposed to extreme heat stress (DHW>8), with 307 individual reefs, making up 10% of the total GBR reef area, repeatedly exposed to this level of heat stress. It is within these reef locations at DHW>8 that most significant shifts in community composition are likely and declines in living coral cover will be most pronounced.

Throughout the northern and central regions of the GBR, levels of coral mortality during the bleaching events of 2016 and 2017 at reefs exposed to a DHW>5 (66% of the total GBR reef area) were quantified to represent a loss of 7-15% of the living coral at the majority of reefs in these heat stress categories (75^{th} percentile), with maximum mortality rates at some reefs (less than 10% of the observations) as high as 97%. The dynamic nature of GBR coral reefs (spatial variation in composition and cover) requires, long-term repetitive surveys, at the same location and depth, and an understanding of the frequency, severity and location of disturbance events to detect and define long-term trends in reef community health, composition and abundance. The co-ordinated monitoring efforts that have been established on the GBR, indicate that the living hard coral cover throughout reefs in the northern and central regions of the GBR in 2017 - 2019 have reached the lowest levels ever recorded by the AIMS Long-Term Monitoring

Program since it began in 1985 (AIMS 2019). Maximum hard coral cover was documented as high as 30% in the northern GBR in 1988 and 25% in the central GBR in 2016 (surveys prior to peak heat stress and bleaching through this region). Average coral cover now in 2019 is at 14% in the north and 12% in the central GBR, following a series of disturbances through these regions by cyclones, COTS and bleaching over the past decade (De'ath et al. 2012; AIMS 2019). Coral cover levels of 27% - 33% represent a meaningful baseline range for coral cover on the GBR prior to 1995 and the major disturbance events that have been documented since (Osborne et al. 2011). The long-term persistence of the GBR, requires individual reef communities throughout the entire ecosystem to recover between episodic and more frequent and severe disturbance events (Donner et al. 2005; Osborne et al. 2011). Prior to 2016, estimated loss of living coral on the GBR due to bleaching was low (~5% (Osborne et al. 2011; De'ath et al. 2012)) and this was likely due to the small spatial footprint of extreme heat during the 1998 and 2002 events (>15% of the GBR reef area). Severely impacted reef communities will require 10-15 years to recover following mass mortality events, with reefs in Western Australia exhibiting an increase in coral cover from 9% to 44% over a 12 year period, with an increase in larval recruitment emerging six years after bleaching mortality (Gilmour et al. 2013). As the spatial footprint and severity of heat stress increases with ocean warming (66% of the GBR reef area DHW>5, 6.7 fold more heat stress than any other major heatwave), the ecological impacts on the coral reefs due to climate change driven heatwaves has increased faster than expected (Donner et al. 2005) and will reduce the likelihood of individual reefs avoiding multiple disturbance events over the next 10-15 year period. As a result, recovery to historic baseline levels along the central and northern reefs of the GBR will be more challenging and unlikely.

4.3 Integrating observations, survey methods and the interpretation of impact

Available in-water datasets used in this study included both quantitative transect based techniques and qualitative estimates using established RHIS based survey techniques. A primary advantage of the RHIS method is that it is a relatively easy technique that can be used widely by a range of reef stakeholders using little equipment. As a result, it increases the number of observations during an event which enables us to capture the onset and development of coral bleaching. However, because most of the RHIS based data is a visual estimate across a relatively large single area (entire area can be out of the view of the observer) within random locations, it makes it more difficult to document change as the bleaching event develops within and between habitats and reefs. The RHIS method is not quantitative and there is an increase in the overall variability in the data within and between DHW categories of heat stress, which limits conclusions and reduces the accuracy of the impact assessment (see range in observations at increasing levels of heat stress (DHW category) in Figure 13). Despite the limitations and increased variability within this dataset, as temperature stress increases, the proportion of RHIS based survey observations recording an increase in the proportion of the community bleached and recently dead also increased. A separate report released using RHIS observations collected by the COTS targeted control program, that was also analysed within this report, revealed community bleaching levels ranging from 25% - 55% in 2016 (RRRC & AMPTO 2016). Documenting the differences between minor to moderate bleaching from severe bleaching and early mortality are important factors in describing the potential impacts to expect from a reef community under bleaching stress. The GBRMPA RHIS manual used by a wide range of observers, including the Cairns-Port Douglas sector report (Reef and Rainforest Research Centre & Association of Marine Park Tourism Operators, 2016) in 2016 classified severely bleached fluorescent colonies as “pale” Category 2, which is incorrect. The Category 2 pale/fluoro scoring in 2016 underestimated the level of severe bleaching throughout the RHIS based observations. For future observations it has been recommended that all future observations by RHIS observers classify all severely bleached corals which could include either totally white or totally white with fluorescent stress responses (Figure 5D and 5E). This change will enable enhanced integration of RHIS based observations with the transect based methods and more accurately capture the severely bleached proportion of the community at risk of mortality during the next bleaching event. To fully document the impacts of coral bleaching events, observations need to ensure that consistent and comparable measures of bleaching severity are used. As the spatial footprint of extreme heat stress anomalies develop, impact assessments need to accurately assess both the proportion of reef corals bleached (% bleaching) and the proportion of severely bleached corals that could cause mortality and loss of living coral cover.

4.4 Impacts of science communication on the perception of current state of the GBR

Accurate messaging regarding the bleaching related impacts on the GBR remains challenging due to the size, scale and diversity of this marine ecosystem. Mass coral bleaching events represent widespread regional responses of reef building corals to temperature extremes above historical summer maximum values for prolonged periods. Although, the spatial footprint of heat stress has increased considerably, 44% of the GBR reef area has avoided severe levels of heat stress (DHW>5), mostly throughout the southern sectors of the GBR, but also within particular locations throughout the northern and central sectors. The goal of all reef industry partners, including science research organizations, management authorities and tourist operators involved in documenting and reporting the impacts of a disturbance event should be to provide a balanced, consistent, realistic message that depicts the full-scale impacts with the entire spatial size and scale of GBR ecosystem perspective. Ensure that local observations of individual reefs and habitats are considered within the context of heat exposure at that location. Clear distinctions between a reef with some minor to moderate bleaching and a reef that has suffered extensive severe bleaching, mortality and loss of living coral cover need to be emphasized. It is this shift in reef communities and loss of hard coral cover due to heat stress that is of most concern.

4.5 Future climate for the reef

The GBR is an iconic ecosystem for Australia and contains significant natural habitats for conservation of biological diversity. The challenges of maintaining the Outstanding Universal Values (OUV) in a rapidly warming climate became evident during the widespread coral bleaching events in 2016 and 2017 (Hughes et al. 2017). Climate change is the biggest threat to the GBR. Global emissions of greenhouse gases, particularly carbon dioxide (CO_2) (GBRMPA 2019) has caused record breaking extreme summer temperatures and ocean warming at a rate faster than previously expected (Hoegh-Guldberg 1999; Donner et al. 2005) and faster than corals can adapt. Research following the first global bleaching event in 1998, projected that coral bleaching would become more frequent and occur two to five times per decade by 2030 (Donner et al. 2005). Recent observations of community wide coral bleaching and mortality across large spatial areas has been driven by only 0.92˚C annual warming compared to pre-industrial temperatures (Lough et al. 2018). Current emissions trajectories combined with temperature stress metrics indicate that the GBR will suffer severe heat stress at levels capable of causing bleaching driven mortality events twice per decade by 2035-2041 and annually by 2044-2051 (Heron et al. 2017). Based on the emissions reduction trends over the past decade, global ocean warming rates remain along the “business as usual” RCP8.5 (Representative Concentration Pathway (Heron et al. 2017)), which means that without urgent global action to curb CO_2 emissions (GBRMPA 2019), this trajectory will result in a global warming rate of +2.6-4.8˚C (Figure 15) by the end of the century (IPCC 2018). Heat stress to these extremes over a relatively short time-frame (50-80 years) would cause heat stress that would be over six times more severe than the heat stress observed in 2016 (Lough et al. 2018). Current trends and model projections indicate that global average temperatures will likely reach +1.5˚C between 2030 and 2052 (IPCC 2018), and the aggregated pledges made by countries under the United Nations Framework Convention on Climate Change (UNFCCC) Paris Climate Agreement would likely result in +3˚C warming by 2100 (Heron et al. 2017). The climate future for coral reefs and the GBR indicate that summer heat anomaly extremes will continue to develop along the length of the GBR and undoubtedly lead to more frequent and severe coral bleaching events.

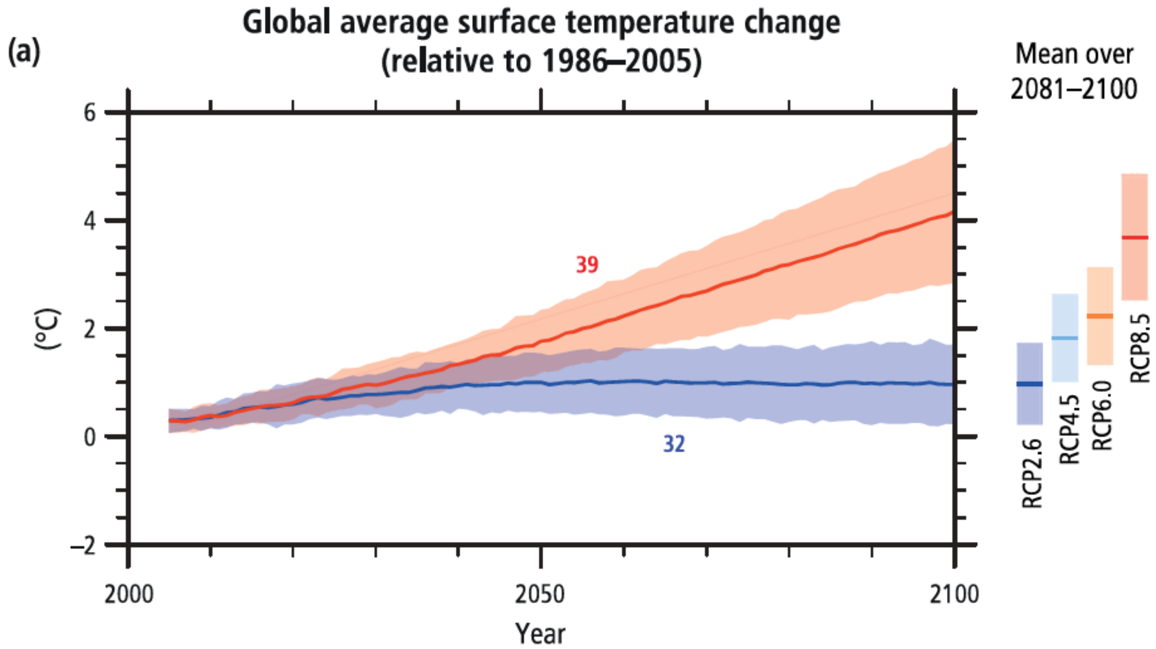


Figure 15: Global average surface temperature change projections from 2006-2100 (relative to 1986-2005 average) based on RCP2.6 (stringent emmissions curbing scenario) and RCP 8.5 (business as usual) Representive Concentration Pathways of greenhouse gas emissions. Mean global surface temperatures for 2081-2100 shown on the right, with end of century temperatures of RCP 6.0 to RCP 8.5, the probable target at present without urgent global initiatives to curb emissions. (Figure from: IPCC 2014).

5.0 CONCLUSIONS AND RECOMMENDATIONS

Recent observations of community wide coral bleaching and mortality has been driven by only 0.92˚C annual warming globally compared to pre-industrial temperatures (Lough et al. 2018). Current trends and model projections indicate that global average temperatures will likely reach +1.5˚C between 2030 and 2052, and result in at least +3˚C warming by 2100 (Heron et al. 2017). Coral reefs throughout the GBR will experience more frequent and extreme ocean heat waves in the future.

Results using satellite remote sensing of ocean temperatures and survey observations of coral bleaching and mortality throughout the entire GBR clearly indicate 6.7 times more reef area was exposed to extreme accumulated levels of heat stress (DHW>5; Figures 5 and 6) during the 2016 and 2017 consecutive bleaching events than any of the previously recorded bleaching events on the GBR (1998, 2002 and 2006). A total of 66% of the GBR reef area was exposed to extreme levels of accumulated heat stress (DHW>5), which caused up to 75% bleaching, and 7-15% mortality across the majority of reefs in these heat stress categories. A reduction in bleaching severity and coral mortality was documented by in-water surveys at deeper reef communities between 7-40m, however temperature anomalies as high as 1.5-1.8˚C above normal summer maximums was documented at 40m in offshore reef habitats.

Efforts to document the impacts of ocean heat waves on coral reefs could be improved with co-ordinated changes to in-water survey approaches. Three main factors clearly contribute to dramatic increases in variability of bleaching estimates within the same reef and at reefs that have been exposed to the equivalent level of heat stress (DHW). These factors include listed in order of influence:

(1) timing of surveys at or near peak heat stress (early March to early April at this stage should be prioritized for response efforts);
(2) site selection (permanent vs random locations); and
(3) survey method.

There is less variability in the bleaching estimates from transect based approaches compared to RHIS based visual estimates as heat stress accumulation increases. However, when site selection is controlled RHIS based techniques can provide reliable and comparable estimates of bleaching severity.

Balanced, consistent and accurate messaging from all research and industry partners involved during the next coral bleaching event should remain a focus to avoid sensational headlines and conflicting perceptions of the state of the ecosystem. Statements should depict the full-scale impact of a disturbance event which consider the entire spatial size and scale of GBR ecosystem, not just single reef locations.

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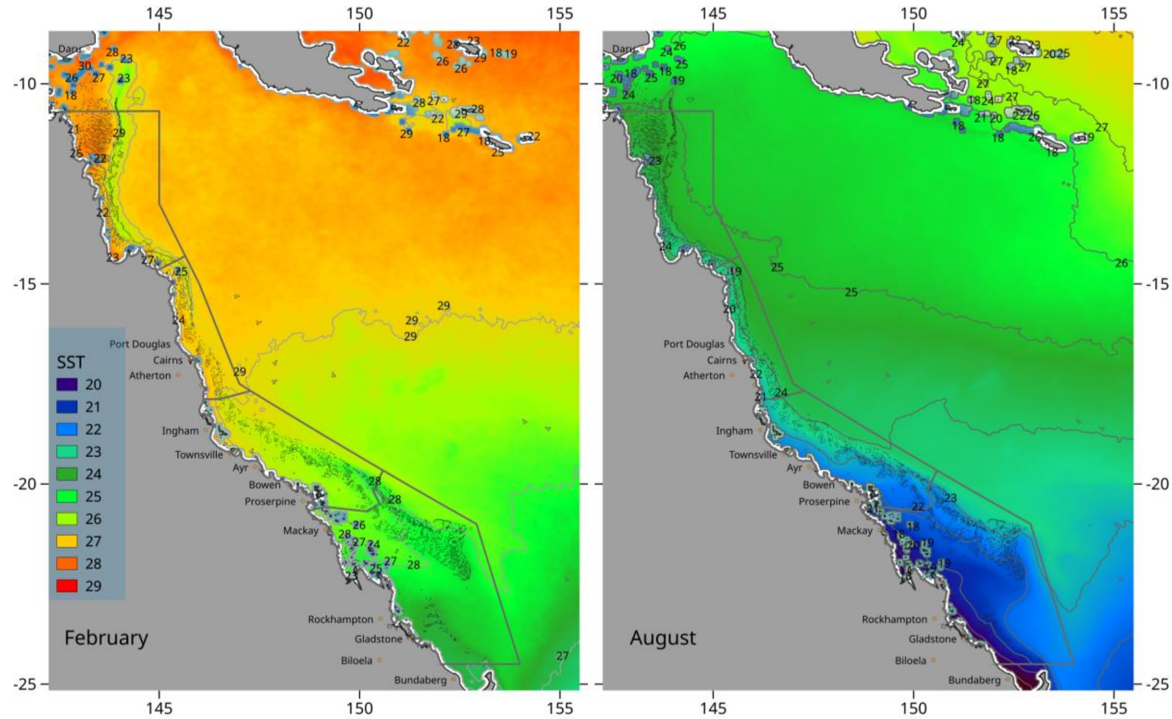
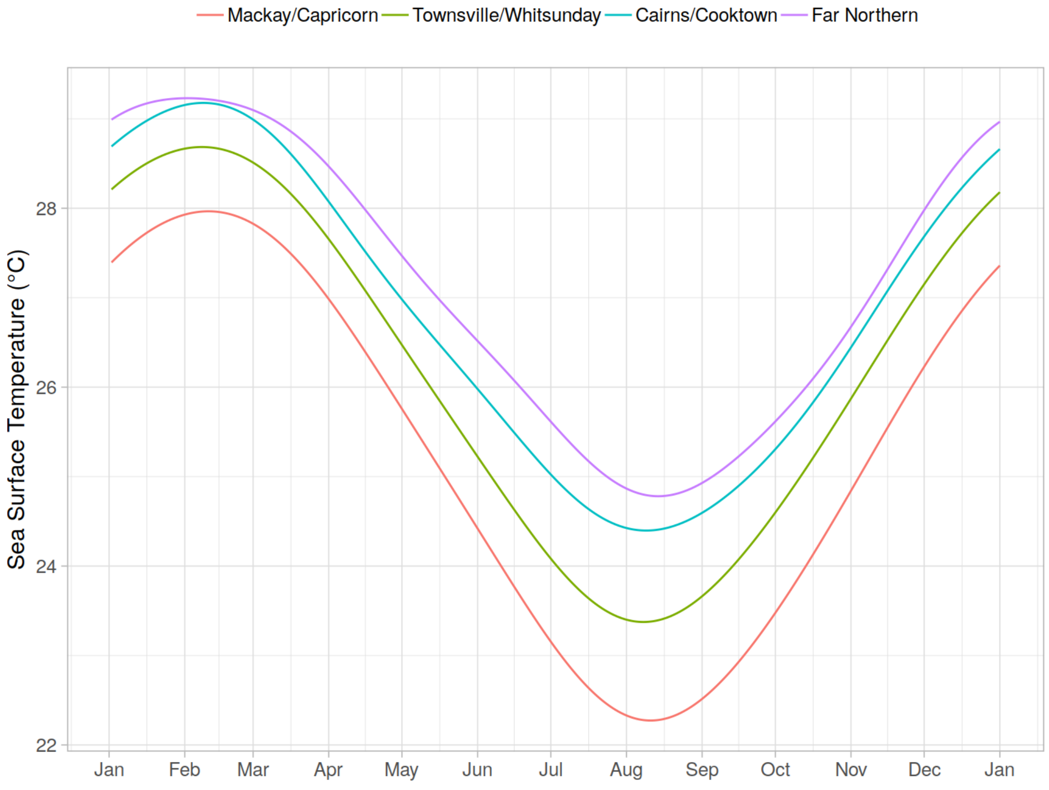
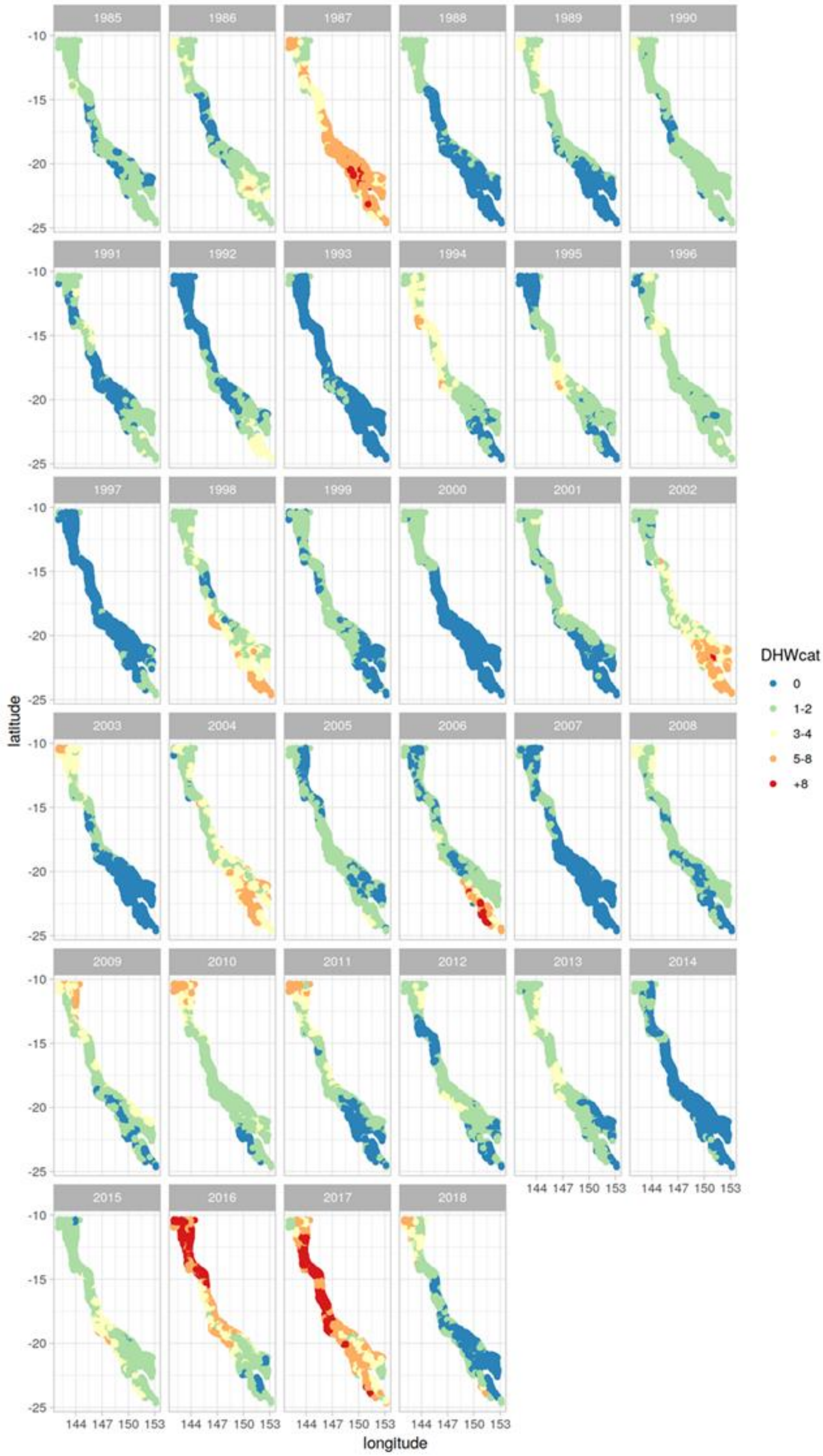
APPENDIX 1: SUPPORTING DATA



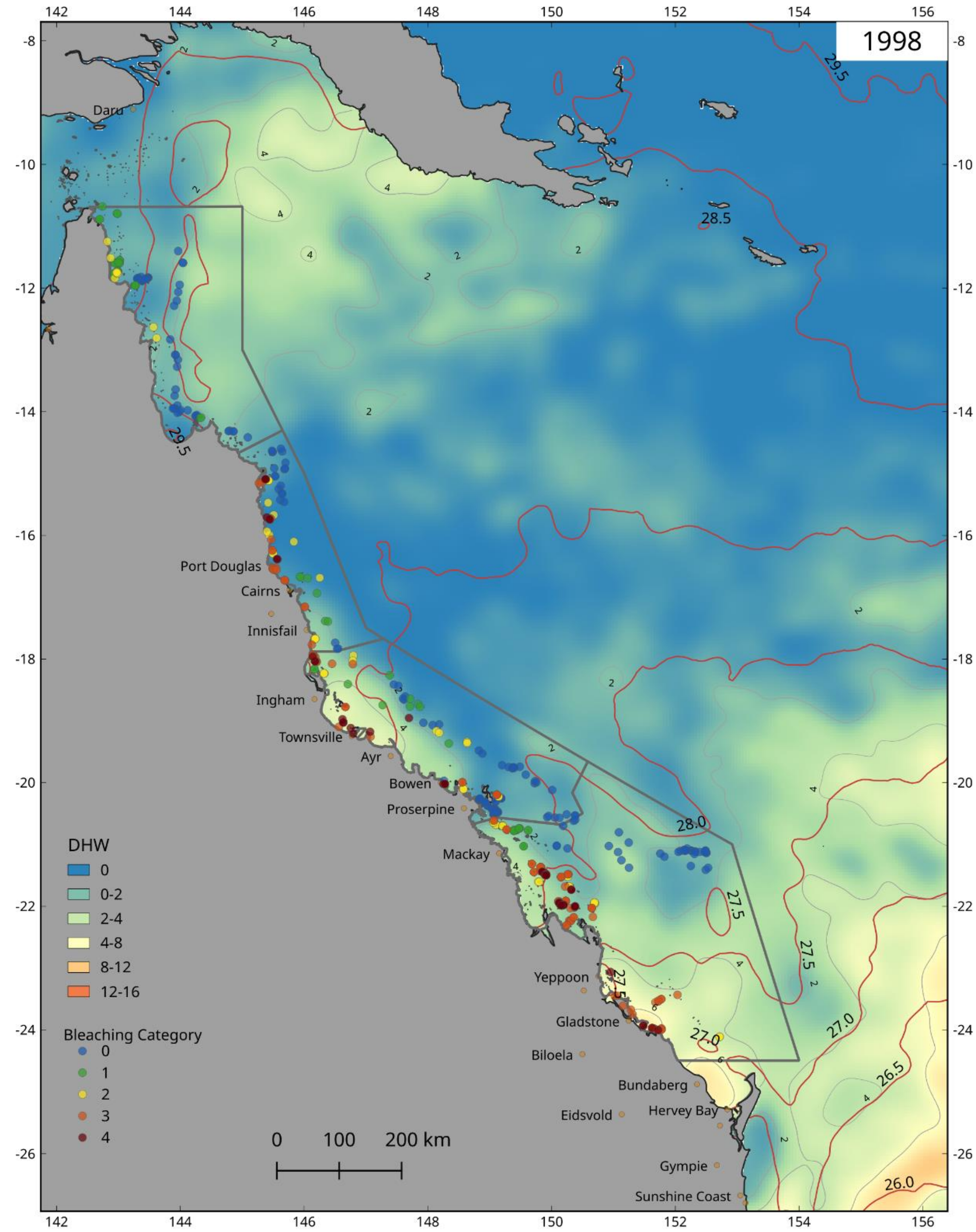
Appendix Figure 1: Historical average summer maximum (February) and winter minimum (August) temperatures across the latitudinal range of the Great Barrier Reef using the Sea Surface Temperature Atlas of Australian Regional Seas (SSTAARS) climatology based on 1.1km resolution, cloud-cleared AVHRR SST data combined with in-situ temperature data from 1992-2016 (Wijffels et al. 2018).



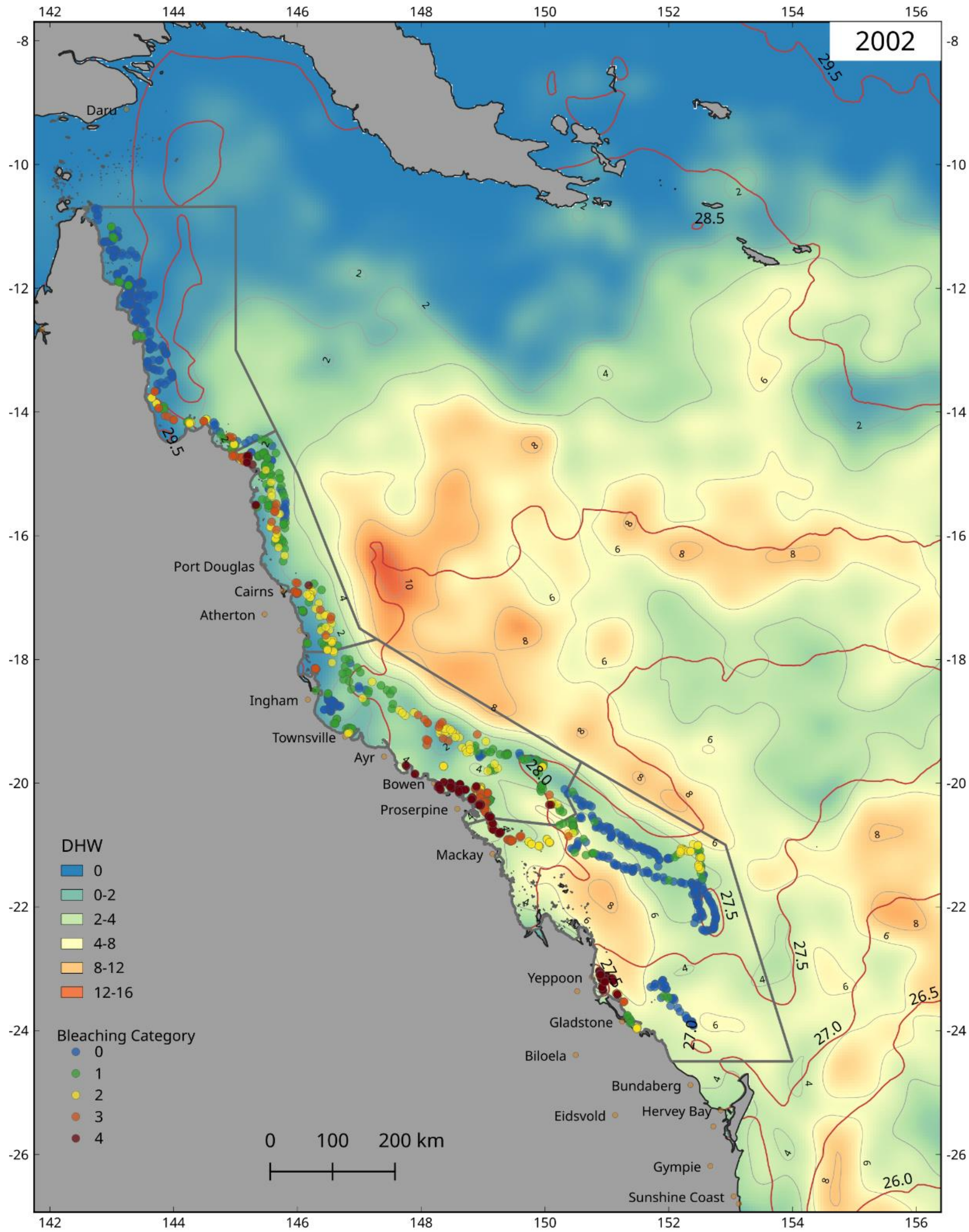
Appendix Figure 2: Daily climatology of sea surface temperature averaged by GBRMPA management sectors [Far northern sector (10-14˚S, max SST 29.23˚C); Cairns/Cooktown (14-18˚S, max SST 29.18˚C); Townsville/Whitsunday Islands (18-21˚S, max SST 28.68˚C); Southern Mackay/Capricorn (21-24˚S, max SST 27.97˚C)]. Historical summer maximum temperatures for each local region represent the local upper thermal limit for coral reefs, periods above this range could cause stress and lead to coral bleaching.



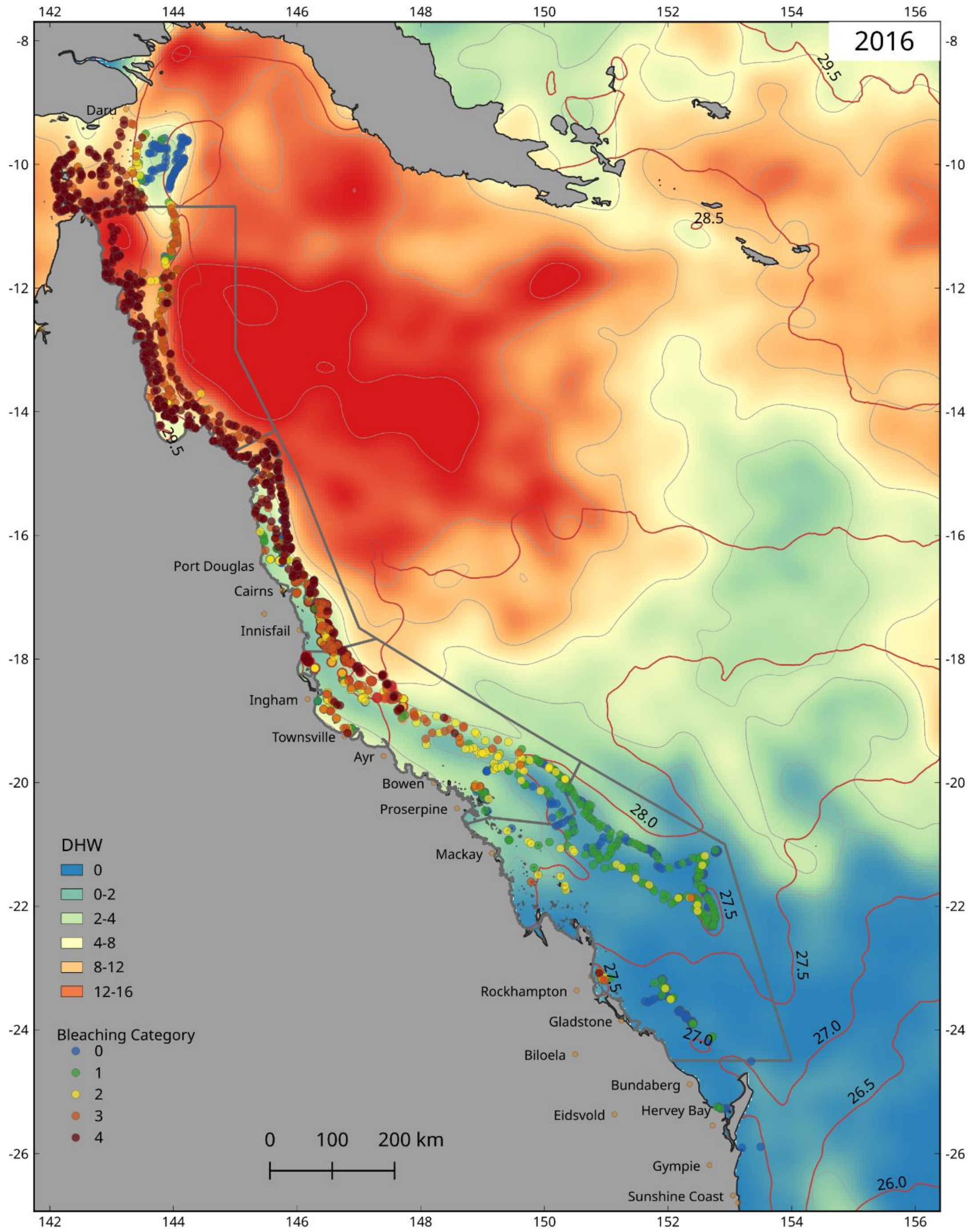
Appendix Figure 3: Annual maximum NOAA Degree Heating Week (DHW; Version 3.1) accumulation of heat stress from 1985 – 2018 along the length of the Great Barrier Reef. No bleaching expected with DHW values from 0-2, minor bleaching at DHW 2-4, major bleaching with some mortality at DHW 5-8 and severe bleaching with potentially extensive mortality at DHW8+.



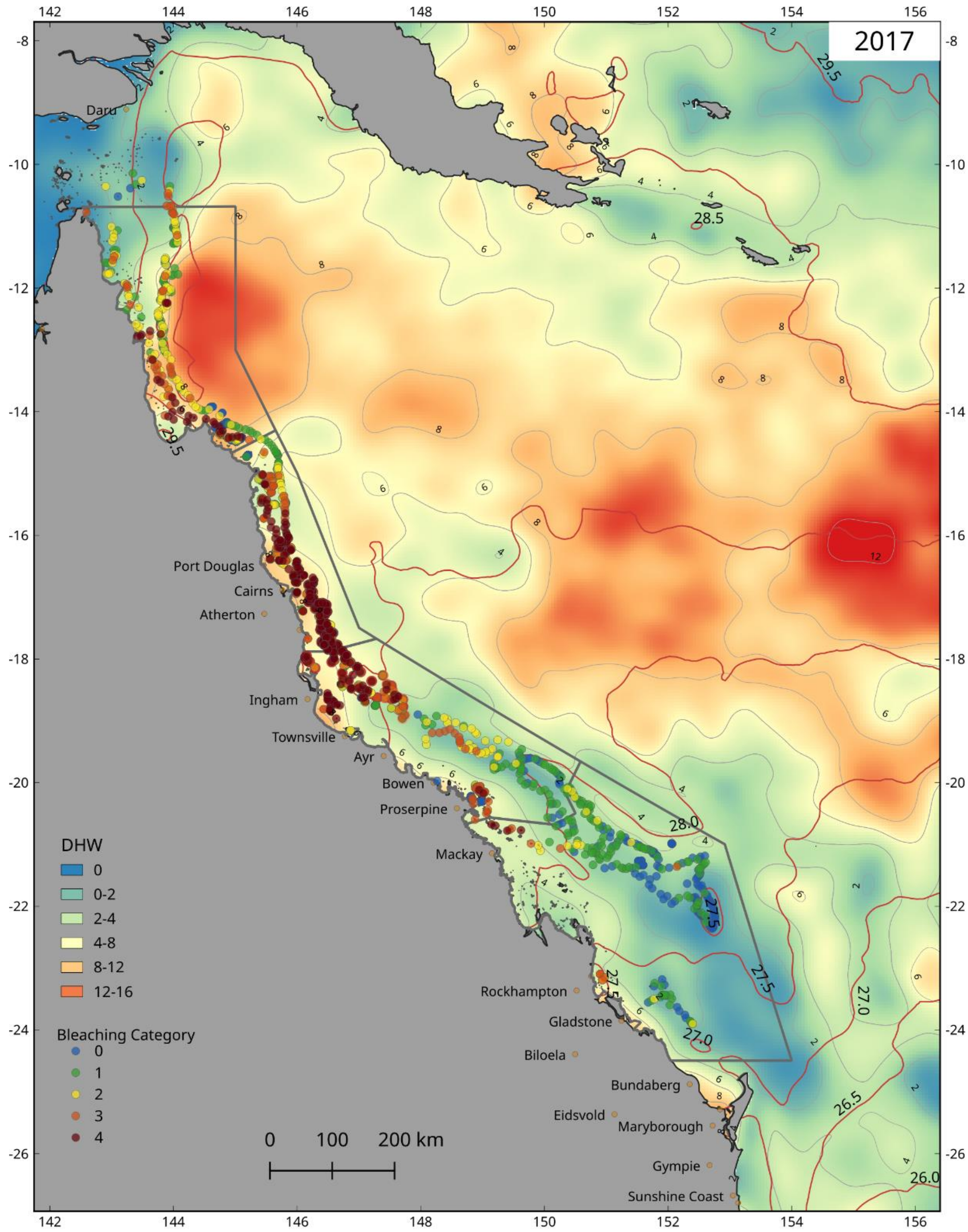
Appendix Figure 4: Spatial distribution of aerial and in water bleaching survey observations in 1998 along the entire length of the GBR. DHW values from 0-2: no bleaching (i.e. normal summer conditions), 2-4: possible bleaching, 5-8: severe bleaching and some coral mortality, >8: extreme bleaching and widespread mortality likely. Community level (combined hard and soft corals) bleaching severity categories: 0 = no bleaching (>1%), 1 = minor (1-10% bleached), 2 = moderate (10-30%), 3 = major (30-60%) and 4 = severe (>60%).



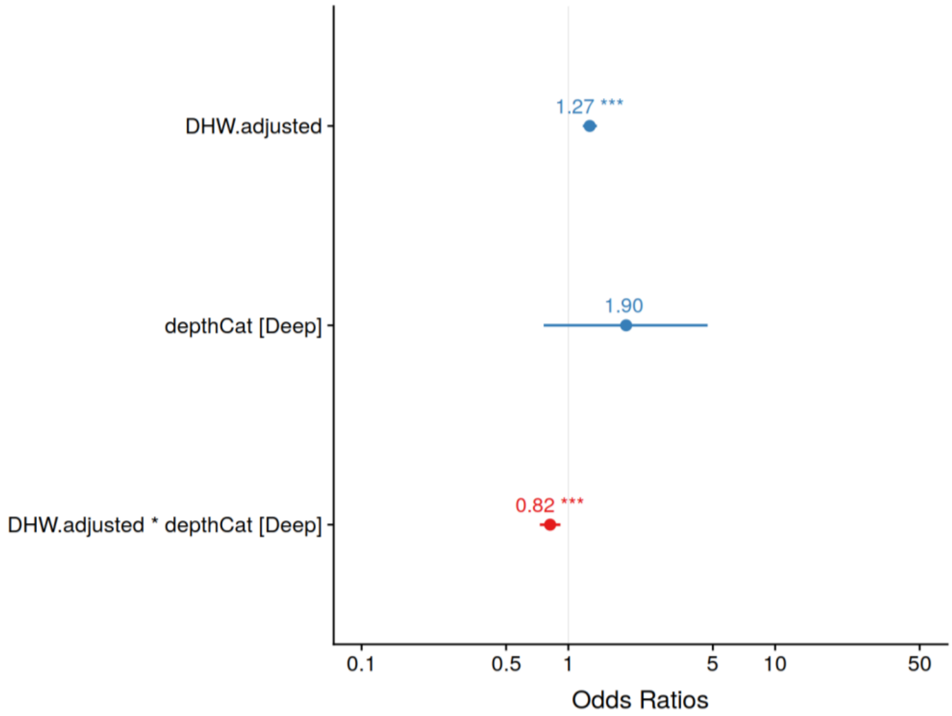
Appendix Figure 5: Spatial distribution of aerial and in water bleaching survey observations in 2002 along the entire length of the GBR. DHW values from 0-2: no bleaching (ie. normal summer conditions), 2-4: possible bleaching, 5-8: severe bleaching and some coral mortality, >8: extreme bleaching and widespread mortality likely. Community level (combined hard and soft corals) bleaching severity categories: 0 = no bleaching (>1%), 1 = minor (1-10% bleached), 2 = moderate (10-30%), 3 = major (30-60%) and 4 = severe (>60%).



Appendix Figure 6: Spatial distribution of aerial and in water bleaching survey observations in 2016 along the entire length of the GBR. DHW values from 0-2: no bleaching (ie. normal summer conditions), 2-4: possible bleaching, 5-8: severe bleaching and some coral mortality, >8: extreme bleaching and widespread mortality likely. Community level (combined hard and soft corals) bleaching severity categories: 0 = no bleaching (>1%), 1 = minor (1-10% bleached), 2 = moderate (10-30%), 3 = major (30-60%) and 4 = severe (>60%).



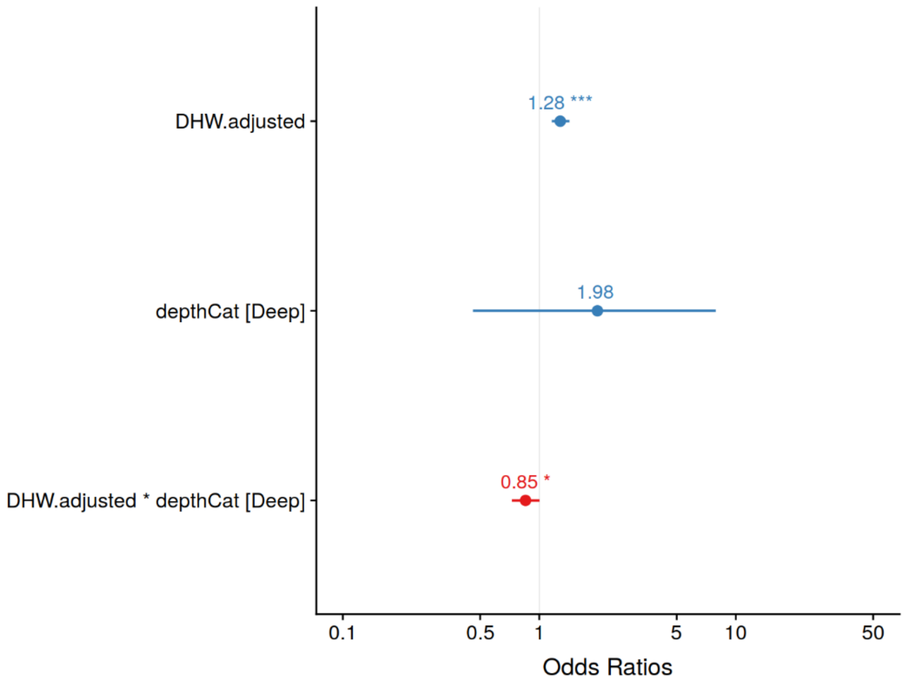
Appendix Figure 7: Spatial distribution of aerial and in water bleaching survey observations in 2017 along the entire length of the GBR. DHW values from 0-2: no bleaching (ie. normal summer conditions), 2-4: possible bleaching, 5-8: severe bleaching and some coral mortality, >8: extreme bleaching and widespread mortality likely. Community level (combined hard and soft corals) bleaching severity categories: 0 = no bleaching (>1%), 1 = minor (1-10% bleached), 2 = moderate (10-30%), 3 = major (30-60%) and 4 = severe (>60%).



Appendix Figure 8: Binomial generalized linear model Odds Ratio plot for community coral bleaching (%) in relation to accumulated heat stress (DHW.adjusted).

Appendix Table 1: Binomial generalized linear model descriptive statistics for the Predictors of % community bleaching with heat stress (DHW.adjusted) and depth as fixed factors.

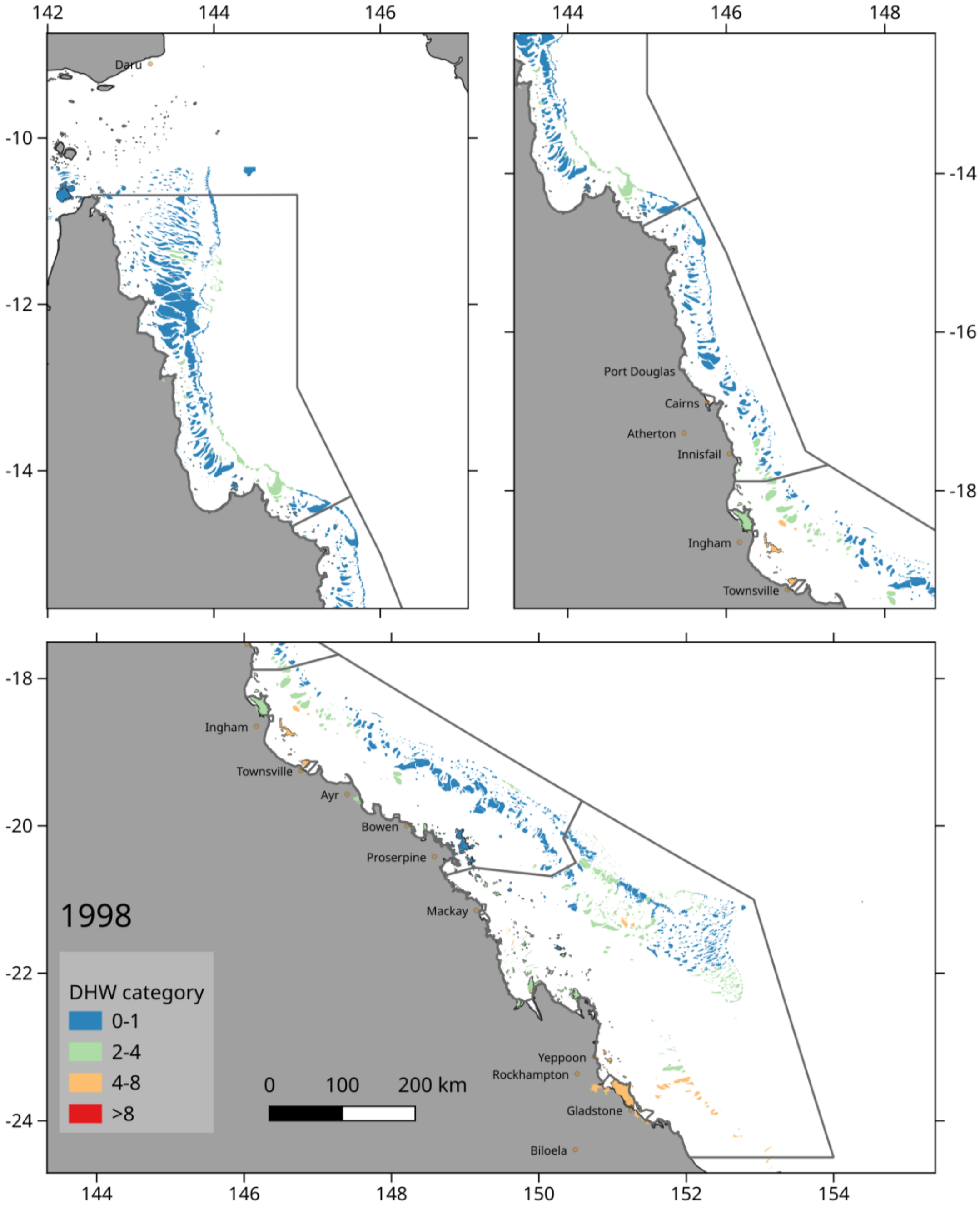
	% Coral Bleached			
Predictors	*Odds Ratios*	*Std. Error*	*CI*	*p*
(Intercept)	0.25	0.28	0.14 – 0.43	**<0.001**
DHW.adjusted	1.27	0.04	1.18 – 1.37	**<0.001**
depthCat [Deep]	1.90	0.46	0.76 – 4.72	0.166
DHW.adjusted * depthCat [Deep]	0.82	0.06	0.73 – 0.92	**0.001**
Observations	576			
Deviance	138.280			
AIC glm goodness of fit (based on deviance)	679.041 27.71%			



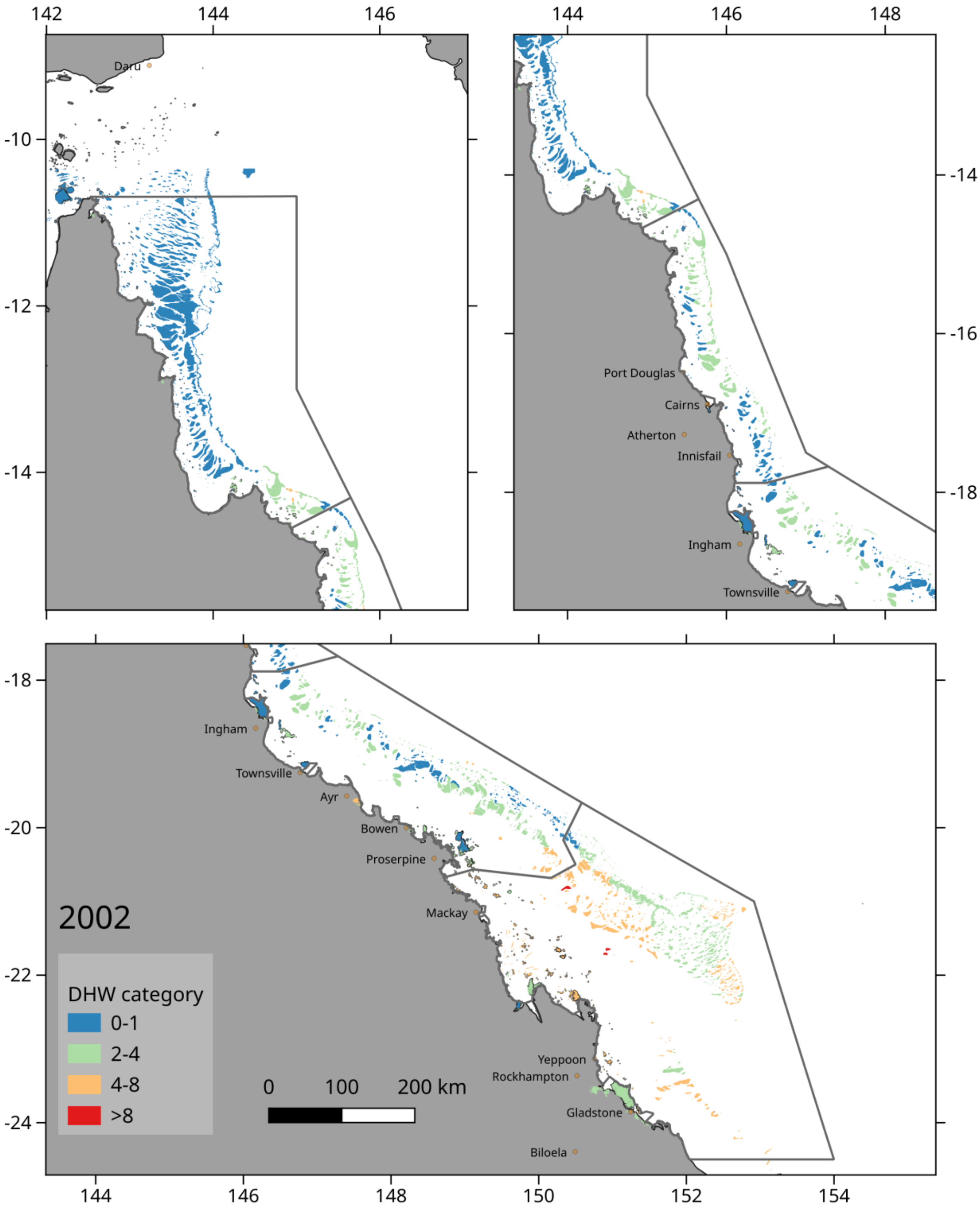
Appendix Figure 9: Binomial generalized linear model odds ratio plots for the proportion of the community (%) that are severely bleached and recently dead (Bleached State 5+6) to accumulated heat stress (DHW).

Appendix Table 2: Binomial generalized linear model descriptive statistics for the Predictors the community (%) that are severely bleached and recently dead (Bleached State 5+6) with heat stress (DHW.adjusted) and depth as fixed factors.

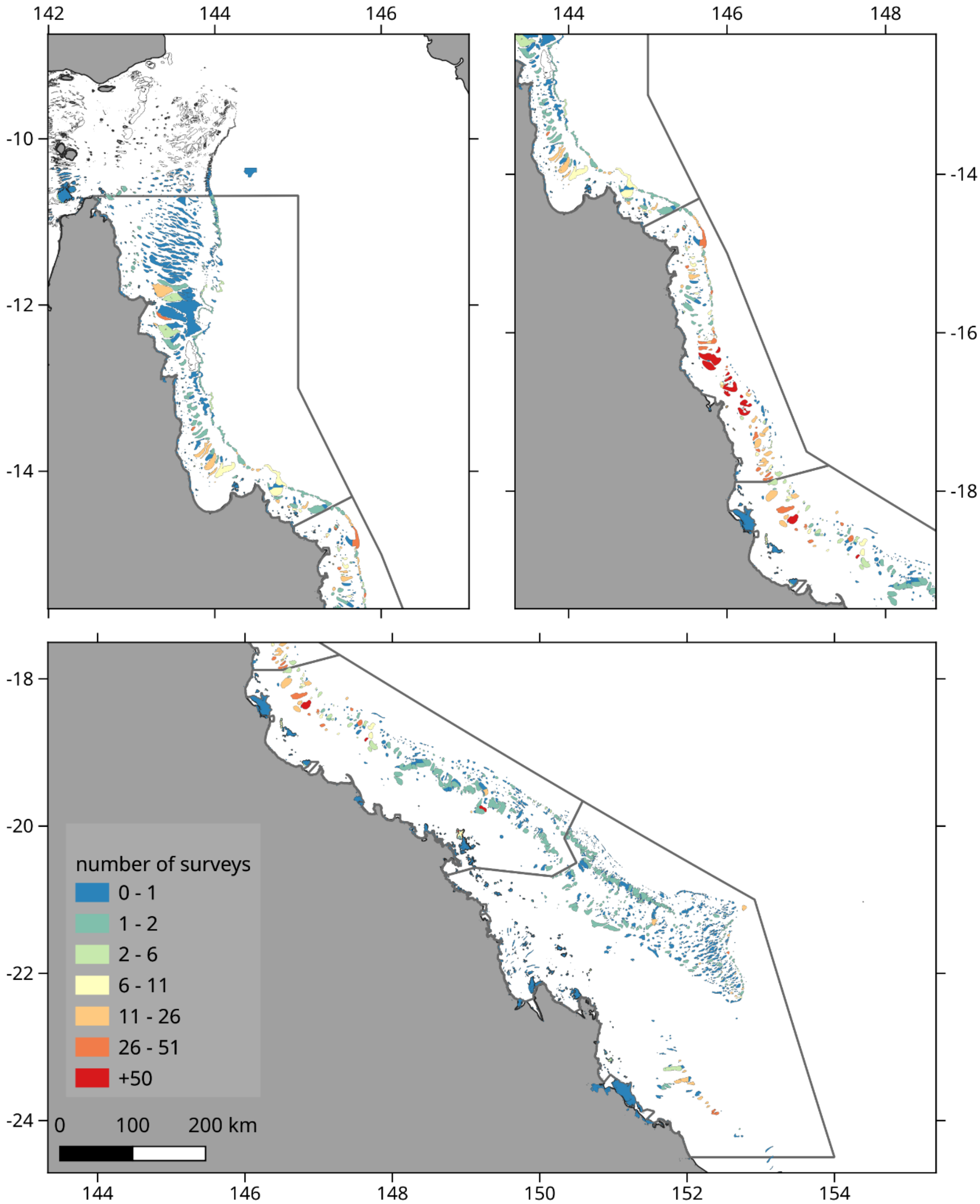
	Severely bleached & recently dead (Bleached State 5+6)			
Predictors	*Odds Ratios*	*Std. Error*	*CI*	*p*
(Intercept)	0.05	0.44	0.02 – 0.11	**<0.001**
DHW.adjusted	1.28	0.05	1.16 – 1.42	**<0.001**
depthCat [Deep]	1.98	0.72	0.46 – 7.90	0.343
DHW.adjusted * depthCat [Deep]	0.85	0.08	0.73 – 1.00	**0.048**
Observations	538			
Deviance	95.567			
AIC glm goodness of fit (based on deviance)	341.331			



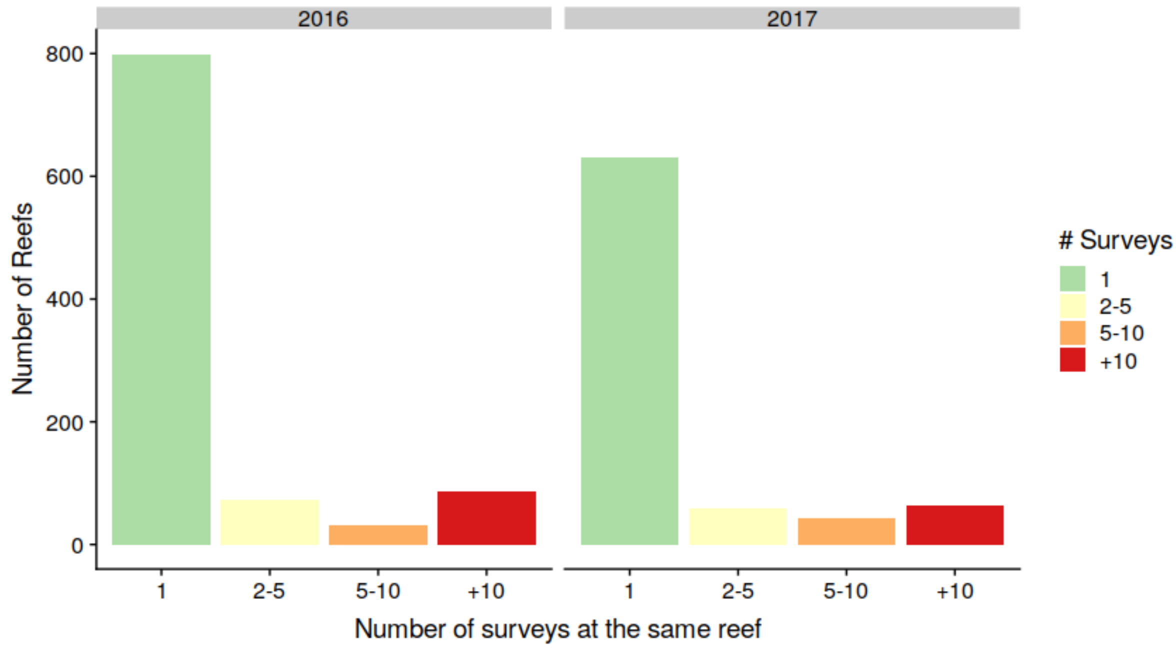
Appendix Figure 10: Maximum Degree Heating Week in 1998 using GBRMPA spatial layer. Based on recent bleaching observations reefs exposed to DHW 2-4 are at risk of minor-moderate bleaching, DHW 5-8 major bleaching and some mortality and DHW>8 severe bleaching and mortality.



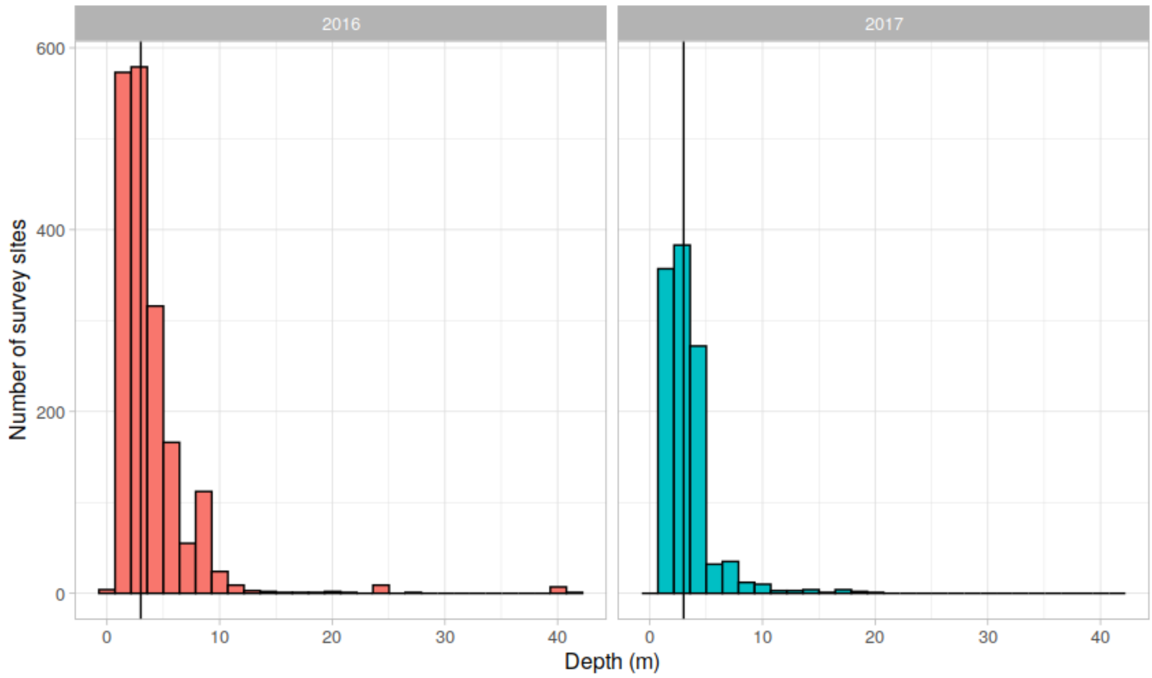
Appendix Figure 11: Maximum Degree Heating Week in 2002 using GBRMPA spatial layer. Based on recent bleaching observations reefs exposed to DHW 2-4 are at risk of minor-moderate bleaching, DHW 5-8 major bleaching and some mortality and DHW>8 severe bleaching and mortality.



Appendix Figure 12: Spatial map of all GBR reefs surveyed by in water or aerial observations categorised by the number of survey observations per reef from 0 to +50 observations from Feb 1 – May 1 in 2016 and 2017 combined.

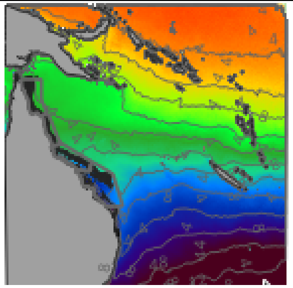
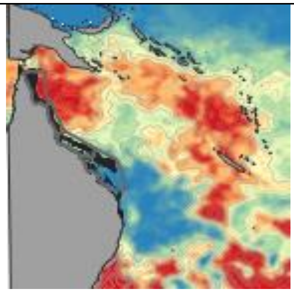


Appendix Figure 13: Frequency histogram of all GBR reefs surveyed by in water or aerial observations with the total number of survey observations per reef from Feb 1 – May 1 in 2016 and 2017.

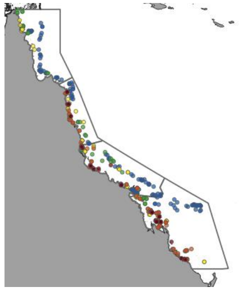


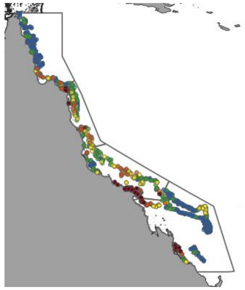
Appendix Figure 1416: In-water bleaching survey observations by depth. Observations made from 0-6m have been categorised as shallow and below 6m as deep in all subsequent analyses.

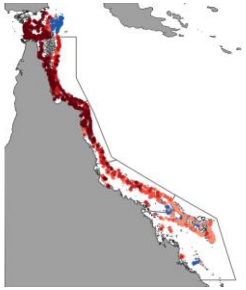
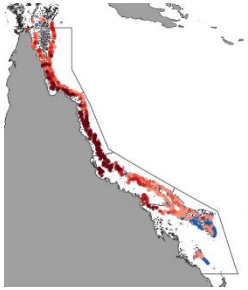
APPENDIX 2: DATA SOURCES

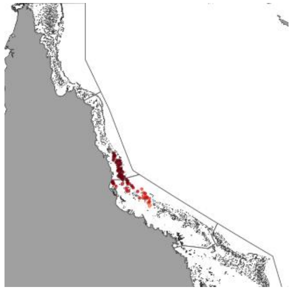
SEA SURFACE TEMPERATURE	DESCRIPTION	SOURCE	REFERENCES
 SSTAARS Climatology	Daily climatological values of Sea Surface Temperature for Australia. Using 25 years of satellite estimated SST, the authors provided a detrended, daily climatological values of Australia sea at 2km of spatial resolution.	http://thredds.aodn.org.au/thredds/catalog/CSIRO/Climatology/SSTAARS/2017/catalog.html	Wijffels, S. E., Beggs, H., Griffin, C., Middleton, J. F., Cahill, M., King, E., … Sutton, P. (2018). A fine spatial-scale sea surface temperature atlas of the Australian regional seas (SSTAARS): Seasonal variability and trends around Australasia and New Zealand revisited. Journal of Marine Systems, 187, 156–196. https://doi.org/10.1016/j.jmarsys.2018.07.005
 NOAA-CRW Degree Heating Week (DHW)	The Degree Heating Week is estimated at 5km spatial resolution by accumulating the degrees above the NOAA's estimated climatology in a rolling window of 12 weeks. NOAA-CRW provides daily estimated of DHW and also the maximum DHW for each year.	https://coralreefwatch.noaa.gov/satellite/bleaching5km/index.php PacIOOs THREDDS server: http://oos.soest.hawaii.edu/thredds/dodsC/hioos/satellite/dhw_5km.html	Liu, G., Heron, S. F., Eakin, C. M., Muller-Karger, F. E., Vega-Rodriguez, M., Guild, L. S., … Lynds, S. (2014). Reef-Scale Thermal Stress Monitoring of Coral Ecosystems: New 5-km Global Products from NOAA Coral Reef Watch. Remote Sensing, 6(11), 11579–11606. https://doi.org/10.3390/rs61111579

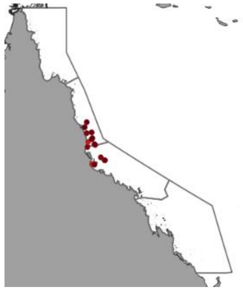
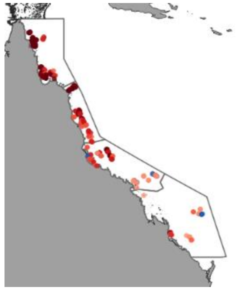
GBR FEATURES POLYGONS	DESCRIPTION	SOURCE	REFERENCES
 GBRMPA - GBR features, inluding Torres Strait	Shape file of polygons of every GBR and Torres Strait feature including major coral reef structures, islands and rocks, coral cays. The data set contains the area in has of every reef feature. An additional layer of features centroids was calculated using QGIS 3.8 centroid algorithm. The centroids were used as geographical reference for the extraction of SST values for every reef.	Data: https://eatlas.org.au/data/uuid/d2396b2c-68d4-4f4b-aab0-52f7bc4a81f5 Metadata record: https://eatlas.org.au/geonetwork/srv/eng/metadata.show?uuid=d2396b2c-68d4-4f4b-aab0-52f7bc4a81f5&currTab=complete	Lawrey, E. P., Stewart M. (2016) Mapping the Torres Strait Reef and Island Features - Extending the GBR Features (GBRMPA) dataset. Report to the National Environmental Science Programme. Reef and Rainforest Research Centre Limited, Cairns (117pp.). Great Barrier Reef Marine Park Authority (2007). Great Barrier Reef (GBR) Features (Reef boundaries, QLD Mainland, Islands, Cays, Rocks and Dry Reefs) (GBRMPA), [Dataset]. Queensland, Australia: eAtlas Repository. https://eatlas.org.au/data/u...e4a8fac3c

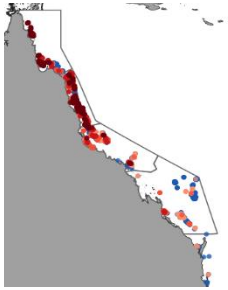
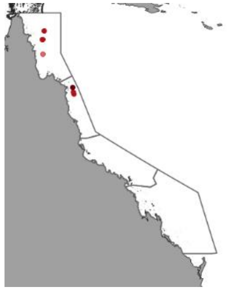
CORAL BLEACHING SURVEYS: AERIAL	**DESCRIPTION**	**SOURCE**	**REFERENCES**
 Berkelmans 1998	Aerial survey of the GBR during the 1998 bleaching event Method: Aerial survey Dates: 1998-03-09 Number of sites: 495 reefs Reported metrics: Reef community bleaching categories as a proportion of the visible living coral cover. The data was presented with five-point rating (1-5) but converted to align with the Hughes dataset format (Category 0-4): <u>Berkelmans</u> <u>Hughes</u> 5 (<1% bleached) = 0 4 (1–10% bleached) = 1 3 (10–30% bleached) = 2 2 (30–60% bleached) = 3 1 (>60% bleached) = 4	https://eatlas.org.au/data/uuid/2a17791d-8175-481b-8d31-c25f02e66ef6	Berkelmans R, De'ath G, Kininmonth S, Skirving WJ (2004) A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns, and predictions. Coral Reefs 23: 74–83

CORAL BLEACHING SURVEYS: AERIAL	**DESCRIPTION**	**SOURCE**	**REFERENCES**
 Berkelmans 2002	Aerial survey of the GBR during the 2002 bleaching event Method: Aerial survey Dates: 2002-03-20 Number of sites: 1295 reefs Reported metrics: Reef community bleaching categories as a proportion of the visible living coral cover that is bleached. The data was originally presented with five-point rating (1-5) but converted to align with the recent Hughes dataset form (Aerial Bleaching Categories 0-4): Berkelmans Hughes 5 (<1% bleached) = 0 4 (1–10% bleached) = 1 3 (10–30% bleached) = 2 2 (30–60% bleached) = 3 1 (>60% bleached) = 4	https://eatlas.org.au/data/uuid/2a17791d-8175-481b-8d31-c25f02e66ef6	Berkelmans R, De'ath G, Kininmonth S, Skirving WJ (2004) A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns, and predictions. Coral Reefs 23: 74–83

CORAL BLEACHING SURVEYS: AERIAL	**DESCRIPTION**	**SOURCE**	**REFERENCES**
 Coral Bleaching Aerial Survey: Hughes 2016	Aerial survey of the GBR during the 2016 bleaching event Method: Aerial survey Dates: 206-03-22/2016-04-28 Number of sites: 924 reefs Reported metrics: Reef community bleaching categories as a proportion of the visible living coral cover. Aerial Bleaching Categories: 0 =<1% bleached 1 = 1–10% bleached 2 = 10–30% bleached 3 = 30–60% bleached 4 = >60% bleached	ARC Centre of Excellence for Coral Reef Studies, James Cook University Torres Strait Regional Authority	Hughes, T.P., Kerry, J.T. and Simpson, T. (2018), Large-scale bleaching of corals on the Great Barrier Reef. Ecology, 99: 501-501. doi:10.1002/ecy.2092
 Coral Bleaching Aerial Survey: Hughes 2017	Aerial survey of the GBR during the 2017 bleaching event Method: Aerial survey Dates: 2017-03-15 / 2017-04-05 Number of sites: 725 reefs Reported metrics: Reef community bleaching categories as a proportion of the visible living coral cover. Aerial Bleaching Categories: 0 =<1% bleached 1 = 1–10% bleached 2 = 10–30% bleached 3 = 30–60% bleached 4 = >60% bleached	ARC Centre of Excellence for Coral Reef Studies, James Cook University	Hughes, T.; Kerry, J. (2018). Ecological memory modifies the cumulative impact of recurrent climate extremes. James Cook University. (dataset). http://dx.doi.org/10.25903/5beb6e4173f88

CORAL BLEACHING SURVEYS: AERIAL	DESCRIPTION	SOURCE	REFERENCES
 Coral Bleaching Aerial survey: AIMS 2017	Aerial survey of the GBR during the 2017 bleaching event Method: Aerial survey Dates: 2017-03-09 Number of sites: 70 reefs Reported metrics: Reef community bleaching categories as a proportion of the visible living coral cover. Category 0-4	Great Barrier Reef Marine Park Authority. Contact: Rachel Pears Australian Institute of Marine Science Contact: Neal Cantin	Cantin, N. E., Klein-Salas, E., Frade, P. (2021) *Spatial variability in coral bleaching severity and mortality during the 2016 & 2017 GBR coral bleaching event.* Report to the National Environmental Science Program. Reef and Rainforest Research Centre Limited, Cairns (64pp.).

CORAL BLEACHING SURVEYS: IN WATER	DESCRIPTION	SOURCE	REFERENCES
 AIMS 2016	In water survey of reefs in the Townsville-Cairns area in 2016 Method: in water – 1m belt Transect Dates: 2016-03-02 / 2016-04-06 Number of sites: 27 reefs Reported metrics: Bleaching categories 1-4, % Mortality, % Bleaching	Australian Institute of Marine Science Contact: Cantin, N.E.	Cantin, N. E., Klein-Salas, E., Frade, P. (2021) *Spatial variability in coral bleaching severity and mortality during the 2016 & 2017 GBR coral bleaching event.* Report to the National Environmental Science Program. Reef and Rainforest Research Centre Limited, Cairns (64pp.).
 AIMS 2017	In water survey of reefs in the Townsville-Cairns area in 2017 Method: in water – 1m belt Transect Dates: 2017-03-14 / 2017-04-01 Number of sites: 19 reefs Reported metrics: Bleaching categories 1-4, % Mortality, % Bleaching	Australian Institute of Marine Science – Contact: Cantin, N.E.	Cantin, N. E., Klein-Salas, E., Frade, P. (2021) *Spatial variability in coral bleaching severity and mortality during the 2016 & 2017 GBR coral bleaching event.* Report to the National Environmental Science Program. Reef and Rainforest Research Centre Limited, Cairns (64pp.).
 GBRMPA 2016	In water survey of reefs in the GBR area in 2016 Method: in water - RHIS Dates: 2016-03-02 / 2016-06-11 Number of sites: 102 reefs Reported metrics: Bleaching categories 1-4, % Mortality, % Bleaching	Great Barrier Reef Marine Park Authority. Contact: Pears R.	GBRMPA Eye on the Reef data download through Creative Commons licence.

CORAL BLEACHING SURVEYS: IN WATER	DESCRIPTION	SOURCE	REFERENCES
 EotR 2015-2017	Eye on the Reef CoTS Control team observers in water survey of reefs in the GBR area in 2016/2017 Method: in water – RHIS (5m radius) Dates: 2016-02-01 / 2017-04-30 Number of sites: 1200 reefs Reported metrics: Bleaching percent by coral type, Mortality percent by coral type, % Bleaching, % Mortality	Eye on the Reef program submission by the Association of Marine Park Tourism Operators (AMPTO) COTS Control team observations. Contact: Westcott, D.	GBRMPA Eye on the Reef data download through Creative Commons licence.
 Frade 2016	Local survey up to 40m depth to test depth as refuge for bleaching. Method: in water – 1m belt Transect Dates: 2016-05-14/23 Number of sites: 6 reefs / 9 sites Reported metrics: Bleaching categories 1-4	https://github.com/pimbongaerts/monitoring	Frade, P. R., Bongaerts, P., Englebert, N., Rogers, A., Gonzalez-Rivero, M., & Hoegh-Guldberg, O. (2018). Deep reefs of the Great Barrier Reef offer limited thermal refuge during mass coral bleaching. *Nature Communications*, *9*(1), 1–8. https://doi.org/10.1038/s41467-018-05741-0
 Baird 2016	Local survey up to 27m depth to test depth as refuge for bleaching. Method: in water – 1m belt Transect Dates: 2016-04-11/14 Number of sites: 7 reefs / 11 sites Reported metrics: Bleaching categories 1-6 to genus level coral ID	From the author.	Baird, A. H., Madin, J. S., Álvarez-Noriega, M., Fontoura, L., Kerry, J. T., Kuo, C.-Y., … Hughes, T. P. (2018). A decline in bleaching suggests that depth can provide a refuge from global warming in most coral taxa. *Marine Ecology Progress Series*, *603*, 257–264. https://doi.org/10.3354/meps12732

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