Dear Christine and Georgia,
During the public hearing of the Senate Inquiry into the impacts of climate change on marine fisheries and biodiversity in Townsville on 30 August I indicated that I would send the Committee the most recent estimates of coral mortality on the Great Barrier Reef from the 2016 bleaching event, and if possible any estimates from the 2017 bleaching event. I sincerely apologise for the time it has taken me to send you this information as I have been trying to source the most up to date estimates, and have been out of email contact for a few weeks. Below I provide a summary of the current estimates of coral mortality for the 2016 bleaching from the ARC Centre of Excellence for Coral Reef Studies and the Great Barrier Reef Marine Park Authority, and attach some relevant scientific papers and government reports.

ARC Centre of Excellence for Coral Reef Studies: Throughout the entire Great Barrier Reef, including the southern third of the Reef where heat exposure was minimal, we estimate that the total cover of reef crest corals declined by 30.0% between March and November 2016. This estimate is based on in water surveys of corals during and 8-months after the bleaching event. Two alternative approaches for estimating large-scale loss of cover, both based on before-after underwater surveys yield consistent results – a 27.7 or 29.0% decline after 8 months (the latter uses both CoE and GBRMPA data). Importantly all three metrics are in strong agreement. The following press release (https://www.coralcoe.org.au/media-releases/life-and-death-after-great- barrier-reef-bleaching) and conversation article (http://theconversation.com/how-much-coral- has-died-in-the-great-barrier-reefs-worst-bleaching-event-69494) provides detail of the spatial variation in mortality along the GBR. Another useful resource that compares the footprint of the 2016 and 2017 belaching events (https://theconversation.com/back-to-back-bleaching-has-now- hit-two-thirds-of-the-great-barrier-reef-76092)

GBRMPA: The GBRMPA originally released an estimate of 22% coral mortality for the GBR (June 2016), however subsequently revised this up to 30% mortality (see attached GBRMPA final report – 2016 Coral Bleaching Event on the Great Barrier Reef). This revised estimate is in strong agreement with those of the ARC Centre of Excellence for Coral Reef Studies.

Please do not hesitate to contact me if you have any questions regarding these estimates or require further information.

Best regards,
Andrew

Andrew Hoey, PhD
Senior Research Fellow
President Australian Coral Reef Society Biology Editor – Coral Reefs

ARC Centre of Excellence for Coral Reef Studies
James Cook University
Townsville, QLD 4811

Australian Government
Great Barrier Reef
Marine Park Authority

FINAL REPORT

2016 CORAL BLEACHING EVENT

on the Great Barrier Reef

Final report: 2016 coral bleaching event on the Great Barrier Reef

Findings of a rapid ecological impact assessment and summary of environmental monitoring and incident response

June 2017

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Comments and questions regarding this document are welcome and should be addressed to:

Australian Government
Great Barrier Reef
Marine Park Authority

Great Barrier Reef Marine Park Authority
2–68 Flinders Street
(PO Box 1379)
Townsville QLD 4810, Australia

Phone: (07) 4750 0700
Fax: (07) 4772 6093
Email: info@gbrmpa.gov.au
www.gbrmpa.gov.au

EXECUTIVE SUMMARY

Climate change is internationally-recognised as one of the biggest threats to coral reefs around the world, including the Great Barrier Reef. For the last three years, coral bleaching, due to ocean warming associated with climate change, has impacted coral reefs worldwide. Mass coral bleaching events occur during extended periods of elevated sea surface temperatures and have the potential to result in significant and widespread loss of coral.

The current mass coral bleaching occurring in tropical regions across the world since 2014 is the longest mass bleaching event ever recorded. This is a global event triggered by record-breaking sea surface temperatures caused by climate change and amplified in 2016 by a strong El Niño. The ocean is warmer than at any time since the instrumental record began. For Australia's Great Barrier Reef, this resulted in the worst ever coral bleaching in 2016.

The Great Barrier Reef Marine Park Authority (GBRMPA or 'the agency') has a range of management arrangements in place, including its Reef Health Incident Response System, which was used to predict, forward-plan and respond to the coral bleaching event. Based on early warning tools in 2015, the agency and key partners recognised several months in advance that there would be a high risk of bleaching in the summer of 2016. As the mass bleaching unfolded, the agency triggered its Coral Bleaching Risk and Impact Assessment Plan and, consequently, it's largest-ever in-water monitoring effort. GBRMPA formed an incident management team to coordinate and undertake the surveys, with the team also responsible for logistics, mapping, data analysis, stakeholder information and broader communications. Many collaborations and partnerships supported the incident response, and the agency was also a member of Australia's National Coral Bleaching Taskforce convened by the Australian Research Council (ARC) Centre of Excellence for Coral Reef Studies.

This report covers the coral bleaching that occurred in 2016 on the Great Barrier Reef. It includes the results of two rounds of in-water reef health and impact surveys conducted by GBRMPA and the Queensland Parks and Wildlife Service, partners in the joint Field Management Program. Similar information was provided to the public through regular updates on GBRMPA's website and associated communication tools. The first round of Reef-wide surveys conducted from March to early June 2016 provided a rapid assessment of the spatial extent and severity of the 2016 mass coral bleaching event. The second round of Reef-wide surveys conducted from mid-September to end of November 2016 assessed survivorship approximately six months after the peak bleaching period.

The first round of Reef-wide surveys documented widespread but patchy bleaching of varying levels of severity throughout the Marine Park in 2016. There was a strong latitudinal gradient in bleaching severity, with the most severe bleaching having occurred between the tip of Cape York and just north of Port Douglas (that is, in the remote northern third of the Marine Park). This area experienced the greatest heat stress in 2016, with abnormally high sea surface temperatures persisting for a long period of time and as a result, a substantial amount of severely bleached coral died.

Coral mortality as a result of the coral bleaching in the Marine Park increased substantially during 2016 in areas that experienced the most severe bleaching. The second round of surveys found extreme mortality (more than 75 per cent) of shallow-water corals (to about 10 metres depth) in 16 per cent of survey reefs.

An estimated 29 per cent of shallow-water coral cover was lost during 2016 across the Great Barrier Reef Marine Park. Over 75 per cent of this mortality occurred in the far north — the 600 kilometre stretch between the tip of Cape York and just north of Lizard Island. Bleaching-related coral mortality was highest on inshore and mid-shelf reefs in the far north around Cape Grenville and Princess Charlotte Bay, with 80 per cent loss of shallow-water coral cover recorded on average. Severe bleaching and die-off also occurred at all shelf locations in the Lizard Island region. Bleaching-related coral mortality south of Port Douglas was highly variable among and within reefs. Overall the southern Great Barrier Reef had little or no mortality from bleaching in 2016. These results are consistent with the findings from additional surveys by the ARC Centre of Excellence for Coral Reef Studies, the Australian Institute of Marine Science and the Global Change Institute.

The Great Barrier Reef has typically been able to recover from disturbances. However such severe bleaching will have lasting impacts on the health and resilience of affected reefs, primarily via reductions in the amount of coral, shifts in coral community structure, and flow-on effects for reef fish and invertebrate communities. These impacts have the potential to affect the social and/or economic value of reef sites important to Reef-based industries.

The second round of surveys indicated the coral cover as at November 2016 in the southern half of the Marine Park, where bleaching was generally only minor, remained at similar levels to immediately prior to the mass bleaching event. However, coral cover is expected to have further declined since then by varying amounts across most of the Marine Park due to continued bleaching and additional severe disturbances impacting the Reef only a few months later in 2017. On 10 March 2017, GBRMPA confirmed mass coral bleaching was occurring on the Great Barrier Reef for a second consecutive year. A separate report by GBRMPA covers Reef health impacts in early 2017 including bleaching and cyclone damage; therefore, 2017 bleaching impacts, which are still unfolding, are not covered here. Nevertheless, it is important to recognise the cumulative impacts to the Reef from these multiple severe disturbances over such a short period of time, and other pressures such as poor water quality.

The severity of this bleaching event, and the re-occurrence of bleaching in 2017, reinforce the need for much greater international efforts under the Paris Agreement to rapidly mitigate global climate change, as well as national and local actions to build the Reef's resilience by reducing direct and indirect pressures. Active reef interventions may also play a small role (e.g. to augment recovery at key sites). These efforts are our best insurance for protecting this precious natural icon.

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INTRODUCTION

The future of coral reefs worldwide is under threat from climate change and its associated impacts.[1,2] Increasing atmospheric carbon dioxide and other greenhouse gases (fuelled by human activities particularly fossil fuel emissions) are warming ocean temperatures beyond thresholds in which corals can thrive. One of the responses to severe heat stress is mass coral bleaching — moderate to severe coral bleaching across a large spatial scale. Severe and prolonged bleaching can cause substantial loss of coral.[3,4,5] As corals form the foundation of coral reefs, and provide essential habitat to reef fish and invertebrates[6,7], the loss of coral and reef habitat can reduce the populations of other reef inhabitants.[8] In turn, people, cultural values and businesses that depend on reefs are also affected.

In mid-2014 a global mass-bleaching event began in the north Pacific. It has continued into 2017[*], severely affecting many reef locations across all tropical ocean basins. From 2014 to 2016, record-breaking sea temperatures were observed over several months at various locations throughout the world. These higher than average temperatures were caused by climate change and boosted by a strong El Niño[9,10,11], triggering mass coral bleaching in the Caribbean, Indian and Pacific oceans and Australia's Great Barrier Reef. Many different stressors can cause coral bleaching, including freshwater inundation and poor water quality from run-off. However, heat stress from above-average temperatures is the only known cause of mass coral bleaching.[1,12,13,14] Prior to the 2016 summer, the worst global mass bleaching event occurred in 1998 when up to 16 per cent of the world's area of coral reefs was severely damaged; after which some areas no longer resembled coral reefs.[15] The current event is only the third global mass bleaching on record and has been the longest lasting and most widespread.

Corals reefs are particularly vulnerable to ocean warming as corals can tolerate only a narrow range of temperatures and, when exceeded even by one degree Celsius above the normal summer maximum, corals experience heat stress.[1,16,17] Most corals have microscopic marine algae (called zooxanthellae) living inside their tissue which colours the coral tissue and provides up to 90 per cent of their food. When corals are under stress, this symbiotic relationship breaks down and corals expel the zooxanthellae [18]. As the natural pigments in corals' tissue are often fluorescent, the corals may then display a striking fluorescent hue in pink, yellow, purple or blue.[19,20] If they lack fluorescent pigments — or their fluorescence is not visible to the human eye — they will instead appear bright white due to their underlying skeleton. Although these corals may appear astonishingly vivid, the corals are severely stressed. A fully-white bleached coral and a bright fluorescent bleached coral may have comparable low concentrations of zooxanthellae, and therefore similar bleaching status.

The level of exposure to heat stress largely determines the fate of the coral and overall impacts to the ecosystem.[17] If heat stress is only mild or short-term, bleached corals can recover as indicated by the return of zooxanthellae and hence, regaining their darker colour.[21] However, residual effects of the stressful conditions during the bleaching may

[*] This report covers the Great Barrier Reef during 2016 only. At the time of writing in early 2017, the bleaching event is ongoing, driven by climate change, even though the El Niño Southern Oscillation Index has returned to neutral.

negatively impact coral reproduction for one or two years[5,22,23], slow coral growth and calcification rates[24,25], and increase their susceptibility to disease.[26,27,27]

If heat stress is more severe or prolonged, bleached corals will starve and die within weeks to months. The ecological implications of severe bleaching include a reduction in the abundance of coral, shifts in coral community structure, altered habitat composition, and many other ecosystem flow-on effects.[3,8,13,28,29,30] Some of these impacts may not become apparent until many years after the event.[8] Coral reefs that have high rates of coral death from bleaching are likely to take many years or decades to recover[28,29,31], and can potentially shift from being coral-dominated to algal-dominated.[32,33,34]

Ongoing climate change is expected to increase the frequency and severity of coral bleaching events.[17,35,36] On the Great Barrier Reef prior to 2016, there were two widespread mass bleaching events — in 1998 and 2002.[37,38] Additional more localised bleaching events have also occurred on the Reef (e.g. in 2006). In both of the previous widespread bleaching events it was estimated nearly half of the 3000+ reefs in the Marine Park experienced some bleaching, with about 18 per cent experiencing severe bleaching.[38] However, most corals survived, and in each event available estimates suggest approximately five per cent or less of reefs in the Marine Park experienced high coral mortality. While this indicates the Reef has been resilient to mass bleaching events in the past, the capacity of the ecosystem to recover is likely to diminish as the frequency and intensity of disturbances increases.[39,40,41] Severe bleaching also has various implications for communities and industries that depend on the Great Barrier Reef.[42,43,44]

Bleaching is not the only threat to coral reef habitats and its impacts cannot be viewed in isolation from the legacy impacts of past practices and current pressures. These pressures include severe tropical cyclones, coral predation by the crown-of-thorns starfish, poor water quality and direct use. Research by the Australian Institute of Marine Science shows average coral cover on the Reef fell by approximately 40 per cent between 1985 and 2012, due mainly to several cyclones, outbreaks of crown-of-thorns starfish and mass bleaching. However, between 2012 and 2015, there was an overall 19 per cent relative increase in coral cover (to almost 20 per cent from a low point of about 17 per cent).

The biggest increase during this time was in the southern Great Barrier Reef (Australian Institute of Marine Science, 2016). As exposure to major disturbances in the southern Reef was minimal in these three years (i.e. 2012–2015, noting surveys occurred prior to cyclone Marcia), these results demonstrate the capability of the Reef to recover from past disturbances in the absence of new ones. Reducing other pressures, for example by improving water quality and controlling outbreaks of crown-of-thorns starfish, is crucial to improve the ecosystem's resilience in the face of multiple pressures and supporting recovery following coral bleaching.[31]

The Great Barrier Reef Marine Park Authority (GBRMPA or 'the agency') is responsible for managing the Great Barrier Reef Marine Park, a 344,400 square kilometre multiple-use marine protected area off the north-east coast of Australia. GBRMPA works with a range of partners and stakeholders to manage this area for the future.

Given the implications of severe bleaching, GBRMPA has a responsibility to monitor risks, better understand coral bleaching impacts, and keep the public informed. An interim report released in 2016 [45] presented the preliminary results of the first round of in-water surveys conducted by GBRMPA and the Queensland Parks and Wildlife Service to assess the spatial extent and severity of the 2016 mass coral bleaching event in the Great Barrier Reef Marine Park.

This final report extends the interim report by incorporating findings from the second round of surveys that took place in late 2016 to assess recovery rates and survivorship approximately six months after the peak bleaching period. The Torres Strait also had severe bleaching in 2016, but is beyond the scope of this report.

> In 2017, another mass coral bleaching event is occurring on the Great Barrier Reef.
>
> This unfolding event, and other Reef health impacts in 2017, are reported on in a separate publication available at www.gbrmpa.gov.au

GBRMPA uses its Reef Health Incident Response System[46] and associated plans, specifically the Coral Bleaching Risk and Impact Assessment Plan[47], to respond to coral bleaching. Greater understanding of the impacts and implications of these events is essential to refining and further developing management strategies and policies that give the Reef ecosystem and Reef-based industries the best chance as the climate changes.

ENVIRONMENTAL MONITORING AND INCIDENT RESPONSE

Early warning system to detect heat stress

The agency has an early warning system to predict Reef health risks, including bleaching. Mass coral bleaching is preceded by a series of environmental conditions that can be used to assess the probability of such an event occurring. A number of agencies and research institutions have developed tools, in close collaboration with GBRMPA, to monitor these conditions. These tools predict future conditions and enable near real-time monitoring of conditions conducive to bleaching (for example, sea surface temperature anomalies).

The agency's Eye on the Reef program also routinely assesses information submitted by Reef users for any indications of reef health impacts, including any signs of bleaching within the Marine Park. Key partners in this monitoring network include the marine tourism industry and science partners.

Collectively, these tools provide the early warning system for coral bleaching and include:

- climate forecasts in the months preceding the summer to ascertain the likelihood of bleaching
- near real-time monitoring of temperature stress during the summer to assess bleaching risks and target monitoring efforts

- a monitoring network to detect early signs of bleaching
- detailed site inspections to ground-truth predictions or reports of bleaching and to determine if specific incident response thresholds have been exceeded[1].

In late 2015, GBRMPA informed the public of the high risk of coral bleaching in the Great Barrier Reef in summer 2016.

Pre-summer risk assessment and national taskforce

Before each summer, the agency convenes a workshop to seek expert advice on the probable risks to reef health for the coming summer. Attendees include Marine Park managers, climate and weather scientists, coral reef ecologists, water quality specialists and fishery managers from organisations such as the Australian Bureau of Meteorology, the Australian Institute of Marine Science, the National Oceanic and Atmospheric Administration, the ARC Centre of Excellence for Coral Reef Studies, the University of Queensland, the Queensland Parks and Wildlife Service and the Department of Agriculture and Fisheries.

After reviewing climate outlooks, the workshop attendees conduct a collective risk assessment. The risk assessment for the 2015–16 austral summer (i.e. December 2015 to April 2016) concluded there were high environmental risks to the Great Barrier Reef from possible mass coral bleaching and chronic effects of coral disease, and a very high risk from ongoing crown-of-thorns starfish outbreaks. The highest risk period for mass bleaching was identified as early February to March 2016— a period when the probability for accumulated heat stress to exceed known bleaching thresholds is at its greatest. The public were again informed. Subsequently, the agency monitored predictive tools weekly and regularly reported results to senior decision-makers and stakeholders on the likelihood of summer bleaching.

The agency also joined and contributed to the National Coral Bleaching Taskforce, established by the Centre of Excellence to coordinate the research efforts by marine scientists in the event of mass bleaching across Australia. The taskforce brought together many scientists from 10 institutions across Australia (ARC Centre of Centre of Excellence for Coral Reef Studies, Australian Institute of Marine Science, CSIRO, Great Barrier Reef Marine Park Authority, James Cook University, NOAA, University of Queensland, University of Sydney, University of Western Australia, and WA Department of Parks and Wildlife).

Global pattern of heat stress in 2016

Each of the first six months of 2016 set a record as the warmest respective month globally in the modern temperature record, which dates back to 1880[†]. When combined, this six-month period was also the planet's warmest half-year on record, with an average air temperature of 1.3 degrees Celsius higher than the late 19th century.

June 2016 marked the 14th consecutive month where the monthly global temperature record was broken, the longest such period in the 137-year instrumental temperature record. In addition to the global warming trend, the El Niño in the tropical Pacific had increased global sea surface temperatures since October 2015.

[†] Source: Goddard Institute for Space Studies

Pattern of heat stress for Great Barrier Reef waters in 2016

The 2016 mass coral bleaching on the Great Barrier Reef was triggered by record-breaking sea surface temperatures (Figure 1). The rising temperatures reflect the underlying trend of global ocean warming caused by climate change. In 2016 Great Barrier Reef waters had warmed by approximately 0.80 degree Celsius since 1871, and the rate of warming has accelerated since the 1950s[‡]. A strong El Niño also resulted in reduced monsoon activity and, as a consequence, long periods without cloud cover or strong winds which would typically have offered corals some respite from heat stress.

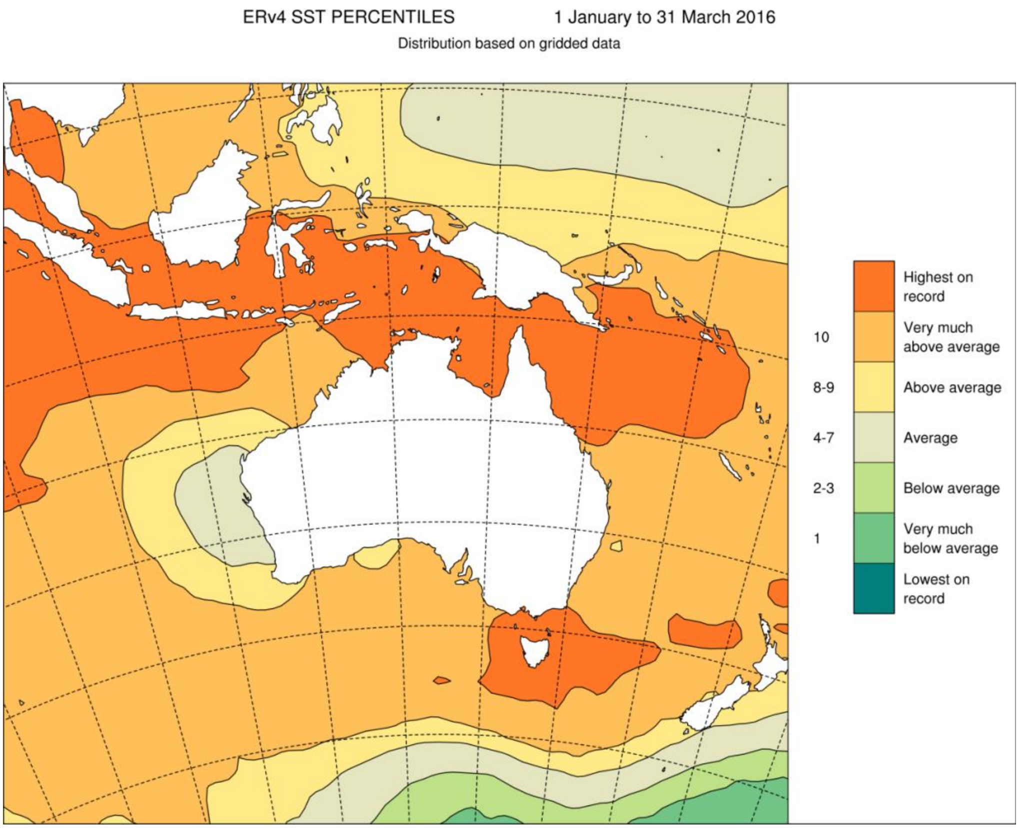

Figure 1 Distribution of record-breaking sea surface temperatures around Australia from 1 January to 31 March, 2016.

Note: "Highest on record" refers to highest sea surface temperature value since 1900. Decile 10 is the highest 10 percent of records — this category is 'very much above average'. Analysis supplied by the Bureau of Meteorology. Based on the ERSST v4 dataset produced by the National Oceanic and Atmospheric Administration. © Australian Bureau of Meteorology

As the El Niño broke down in late summer, warmer waters in the central equatorial Pacific were brought towards Australia, leading to further warming of sea surface temperatures on the Reef.[48]

According to the Bureau of Meteorology, the Great Barrier Reef recorded its hottest-ever average sea surface temperatures for February, March, April, May and June 2016 since records began in 1900, based on the Extended Reconstructed Sea Surface Temperature (ERSST) v4 satellite SST dataset. Each month was 1.0 to 1.3 degrees Celsius higher than

‡ J Lough (AIMS) pers comm. [Using data from HadISST, HadCRUTv4].

the 1961–1990 monthly averages.[48] Importantly, heat stress was not uniform across the Reef over these months§. Local weather patterns, including rain and heavy cloud cover, also influenced regional sea temperatures — the southern half of the Reef experienced late summer cooling due to ex-cyclones Winston and Tatiana. Therefore, some regions avoided the worst of the heat stress and hence severe coral bleaching did not occur there.

Incident response as the coral bleaching event unfolded

GBRMPA uses the Australasian Inter-service Incident Management System** framework to coordinate the governance, planning, operations, logistics, financial and inter-agency liaison arrangements required to adequately respond to a reef health incident.

Information gathered from the early warning system and site inspections helps the agency to understand the severity and spatial extent of impacts. The extent and severity is classified based on the standardised criteria for each incident, and a matrix is used to 'score' the event and inform a detailed situational analysis by the agency's incident management team (Figure 2).

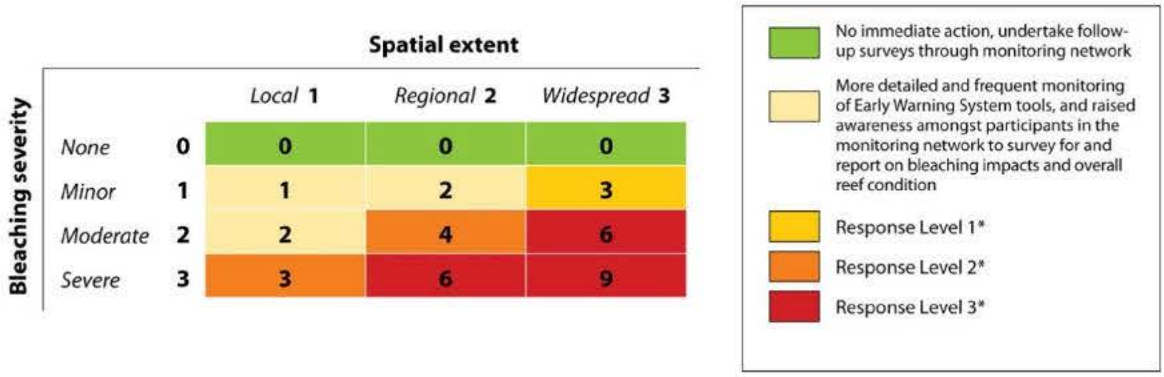

Figure 2 Matrix combining impact severity and spatial extent used to inform a situation analysis.

The situational analysis provides the basis for a decision on the required level of response. There are three potential response levels — 1, 2 and 3. Each increment corresponds to an increase in the severity and spatial extent of the impacts, and the management resources that might be deployed to respond.

By early March 2016, the agency's Eye on the Reef program received reports of minor to moderate coral bleaching in 40 per cent of recent surveys in three of the four management areas (i.e. in Far Northern, Cairns–Cooktown, Townsville–Whitsundays). As a result, GBRMPA declared a coral bleaching response level one under the Coral Bleaching Risk and Impact Assessment Plan.

After in-water site inspections by Reef managers and rangers in the far north revealed severe bleaching and high mortality on inshore and mid-shelf reefs, the agency declared a coral bleaching response level two. Once further site inspections documented moderate to severe bleaching offshore of Townsville, a level three response was declared due to severe regional bleaching and moderate bleaching over multiple management areas.

§ Detailed analyses of reef-scale temperature data are still underway at the time of writing.
** Australasian Fire Authority Council website, 2004, www.afac.com.au

Aerial surveys by the ARC Centre of Excellence for Coral Reef Studies (with participation by a staff member from GBRMPA on many of the flights) were undertaken in March 2016.[31] The aerial surveys provided a rapid Reef-wide assessment of the spatial extent of shallow-water bleaching and proportion of coral cover bleached on 876 reefs within the Marine Park (Figure 3), enhancing situational awareness and helping to direct where in-water survey efforts should be targeted.

This final report summarises the findings of the agency's detailed in-water reef health and impact surveys. These two rounds of surveys enabled a rapid environmental assessment.

Surveys detailed in this report were supplemented by additional surveys by science partners, and complemented by information from tourism industry operators, Indigenous rangers and community members. In particular, the Australian Institute of Marine Science conducted in-water surveys and the ARC Centre of Excellence for Coral Reef Studies conducted aerial and in-water surveys, and the Global Change Institute conducted XL Catlin Surveys of the northern Reef. While all available information on reef health and condition, and the impacts of bleaching, informed the incident response and public updates during the 2016 event, these other data sources are being reported on in other collaborative scientific publications (e.g. [31,49,50]) and additional detailed analyses are ongoing.

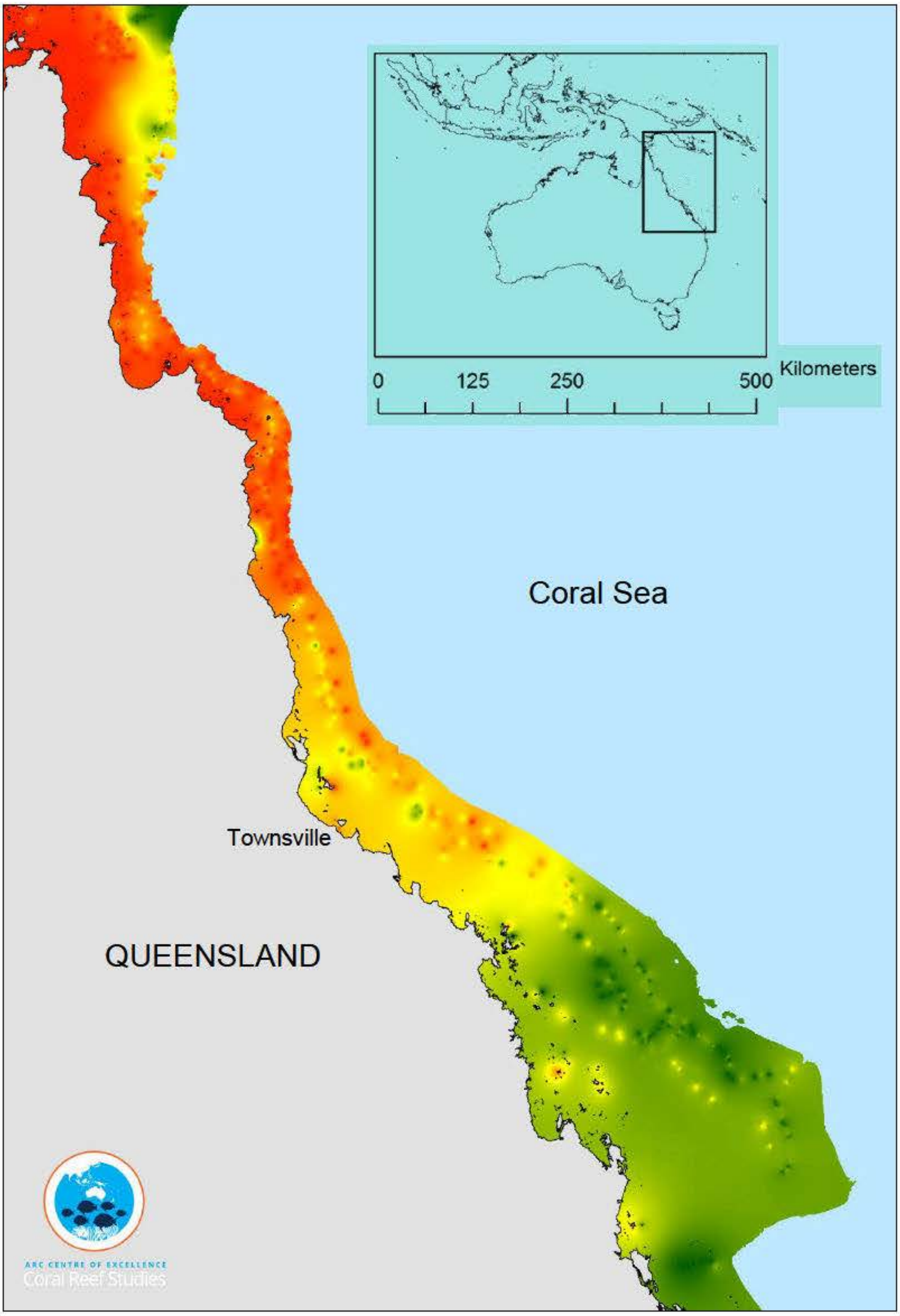

Figure 3 Map showing aerial survey results of coral bleaching during the peak of the bleaching event in March 2016. Source: Australian Research Council Centre of Excellence for Coral Reef Studies.

The footprint of coral bleaching on the Great Barrier Reef in 2016, measured by extensive aerial surveys: dark green (< 1% of corals bleached), light green (1–10%), yellow (10–30%), orange (30–60%), red (> 60%).

SURVEY PLAN AND METHODS FOR BLEACHING IMPACT ASSESSMENT

The Coral Bleaching Risk and Impact Assessment Plan contains an approach to rapidly assess the severity and extent of coral bleaching on up to 45 reefs from the Lizard Island area (off Cooktown) south to the Swains (off Rockhampton), using standard reef health and impact surveys (RHIS).[51] The plan is scalable (e.g. could be applied in one region only for a localised bleaching event) and also recommends additional reefs be included if needed to fully cover an event (e.g. the heat stress extends to areas beyond these 45 reefs).

The plan was modified in 2016 to include the addition of 18 reefs in two northern transects, meaning the final survey plan implemented covered a total of 63 reefs across seven transects (Figure 4). This design covered the whole Marine Park and ensured inclusion of areas that experienced the most significant heat stress and the least heat stress (represented as degree heating days (DHDs), Figure 4) and a representation of cross-shelf and/or latitudinal gradients across/along the Reef.

Where feasible, reefs for which there were historical data through ongoing monitoring programs were chosen, e.g. the AIMS Long-term Monitoring Program. This maximised the value of the RHIS surveys to longer-term studies of reef health and resilience in the face of climate-related disturbances and other impacts such as crown-of-thorns starfish predation.

The seven transects (reef groupings) are located at latitudes centred on 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). Each transect consisted of nine reefs, located on a cross-shelf gradient (i.e., roughly perpendicular to the coast, from inshore to offshore). However, in the Whitsundays only eight reefs were surveyed as poor weather conditions prevented access to the ninth reef. Therefore, a total of 62 reefs were surveyed under the structured assessment reported here in each of two rounds of surveys: “Round 1 from 1 March to 3 June 2016, and Round 2 from 20 September to 27 November 2016.

The 62 reefs are listed in Appendix A. As the Great Barrier Reef Marine Park is divided into four Management Areas (shown on Figure 5), Appendix A also identifies which transects are in each of these Management Areas.

The standard protocol for RHIS surveys[51] was followed. The RHIS survey form is divided into four sections: observer and site details, benthos, impacts and additional information. A copy of the RHIS form is available in Beeden et al. 2014. Key information recorded includes: i) 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). These are 50 metres apart at each location[††].

[††] The survey was carefully designed so that bleaching patterns could be assessed at a range of scales.

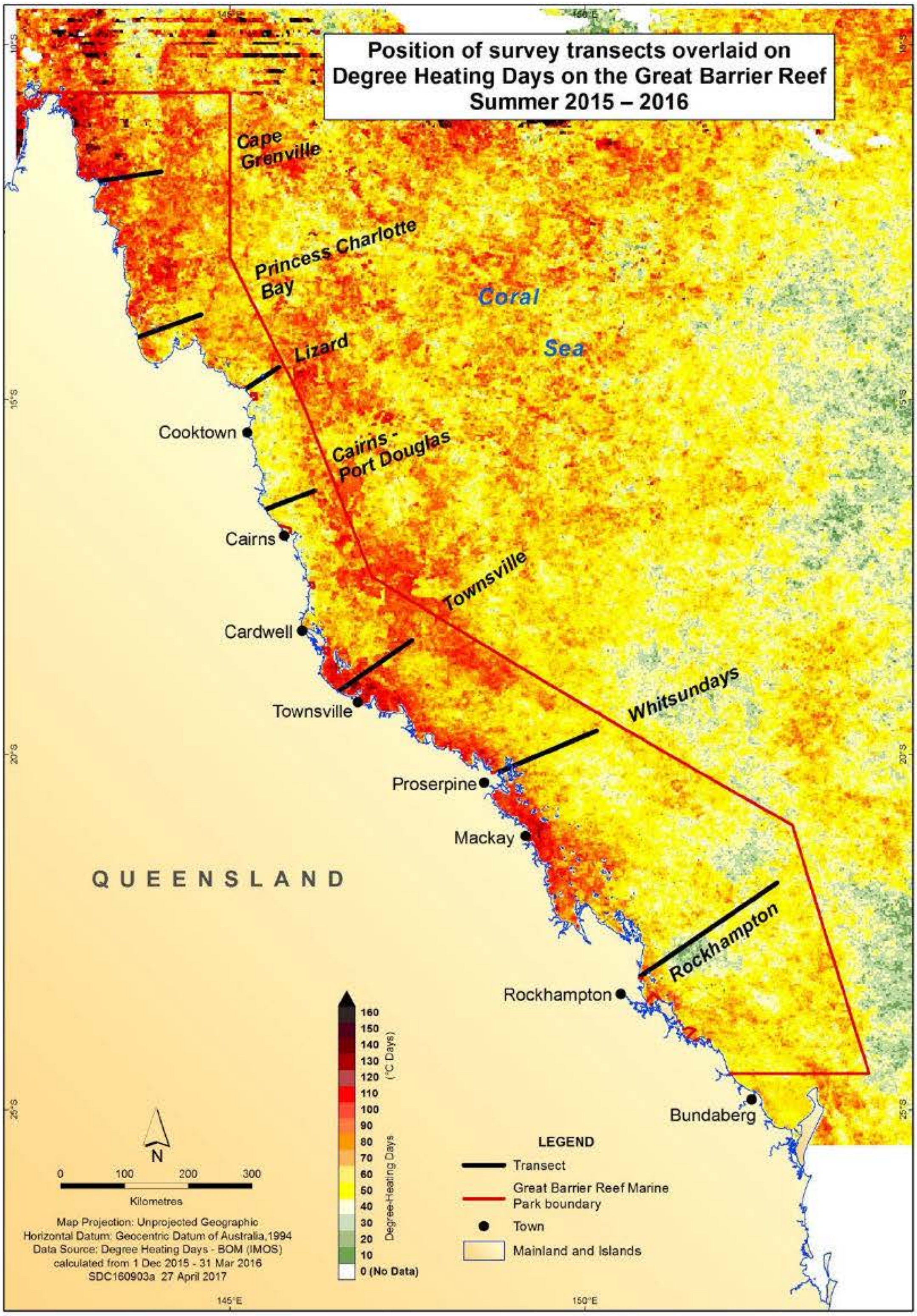

Figure 4 Location of each GBRMPA RHIS survey transect along the length of the Great Barrier Reef overlaid on the pattern of accumulated heat stress for the summer of 2015-2016.

Heat stress of Great Barrier Reef surface waters is measured as Degree Heating Days (DHD) and accumulated over the summer period (1 December - 31 March). One DHD is calculated as one degree Celsius above the local long-term average monthly temperature. If sea surface temperatures exceed the monthly average by two degrees Celsius on a single day, it is counted as two DHDs. Higher DHD counts relate to an increased risk of bleaching. Degree Heating Day data sourced from ReefTemp Next Generation, Bureau of Meteorology.

Three inshore, three mid-shelf and three outer shelf reefs were surveyed in each cross-shelf transect (reef names listed in Appendix A).

To increase assessment reliability, and to capture variability in bleaching patterns within a reef (based on wave exposure and depth), the survey plan aimed to conduct 15 or more RHIS surveys (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 north-eastern 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. Therefore, this assessment was of shallow-water coral habitats only (with surveys covering reef habitat to approximately 10 metres depth).

Survey data was uploaded to the Eye on the Reef system, and analysed daily to 'score' bleaching impact severity[‡‡] at the survey and reef level (Appendix B). The Round 1 results showed the extent and severity of bleaching, which was communicated in near real-time to senior management, government officials, partner organisations, stakeholders and the public.

In Round 1, 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 [51] for each RHIS survey by examining all coral colonies within the point surveys for any impacts. These data were used to categorise the average percentage of coral bleaching mortality for each reef (and recorded as the "observed coral mortality as at June 2016") as follows:

- none (0 per cent)
- low (greater than 0 per cent and less than 10 per cent)
- medium (10 per cent or more and less than 30 per cent)
- high (30 per cent or more and less than 50 per cent)
- very high (50 per cent or more).[§§]

RHIS surveys with no coral present (living or recently dead) were excluded from the analysis of bleaching impacts. Such point surveys typically were in areas with high damage from previous cyclones.

A second round of surveys was conducted after approximately six months to provide an updated assessment of bleaching-related mortality, reef health and resilience following the 2016 mass coral bleaching event. The same RHIS survey protocol was used.

The structured Round 2 surveys (from mid-September to end of November 2016) covered the same 62 reefs across seven transects (Figure 4) examined in Round 1 so that Reef-wide patterns of bleaching mortality could be estimated.

[‡‡] The score given for the severity of the bleaching impact is a composite measure of the impact the stress has had on corals. The four levels of impact (no bleaching, minor impacts, moderate impacts, and severe impacts) are assigned based on a range of factors as set out in Appendix B.
§§ But see below — this category was split into two for Round 2 surveys.

In Round 2, the percentage change in coral cover*** at comparable sites (in terms of depth and aspect) on the 62 transect reefs assessed in both rounds of surveys was used to provide an updated estimate of coral mortality as at November 2016. This was recorded as the "coral loss by November 2016". Due to the unprecedented severity of this event, in Round 2 the upper coral mortality category was further divided into 2 categories:

- very high (50 per cent and less than 75 per cent)
- extreme (75 per cent or more).

The estimated overall loss of shallow-water coral cover from bleaching in 2016 was calculated as follows using data from the structured surveys of transect reefs, which provided balanced representation of reefs throughout the Marine Park.

The Marine Park was divided into seven sectors centred on each survey transect. For each sector, estimated pre-bleach coral cover (mean total coral cover from Round 1 surveys for each of the nine transect reefs) and official GBRMPA reef area data were used to calculate the area covered by corals at the onset of bleaching, in this way taking into account regional patterns in the initial abundance of coral in the estimate. The total loss of coral area for each sector during 2016 was calculated as the product of the pre-bleach coral area and the mean percentage change in coral cover by November 2016. Since the survey data was collected from approximately the first 10 metres of water, this loss is considered to represent shallow-water corals only, and mortality at deeper levels could not be systematically estimated. Estimated losses of coral area for each sector were then summed to give the amount of coral area lost within the Marine Park, and the proportion of total shallow-water coral lost during the 2016 bleaching event.

Coral cover (total cover of hard and soft corals) in early 2016 was estimated from Round 1 surveys for inshore, mid-shelf and outer shelf reefs in each of the seven transects. Similarly, remaining live coral cover (hard and soft corals) in late 2016 was estimated from Round 2 surveys for inshore, mid-shelf and outer shelf reefs in each of the seven transects. Indicative maps of coral cover were produced, based on the assumptions that coral cover and bleaching impacts on reefs within each shelf position and sector were similar to surveyed reefs on average. Early signs of recovery from bleaching were also noted.

Between March and November 2016, each reef was surveyed either once or more. Re-surveying the same reefs provides information on bleaching severity and subsequent bleaching-related mortality or recovery (see time-series photographs in Appendix C).

DETAILED OBSERVATIONS AND RESULTS

Scale and spatial patterns of coral bleaching

Across the Great Barrier Reef in Round 1, all surveyed reefs exhibited bleaching to some degree, however there was high spatial variation in bleaching severity (Figure 5). The severity generally varied in relation to the amount of accumulated heat stress over the summer (Figure 4).

*** Percentage change in coral cover is the difference in cover between the estimated pre-bleach coral cover (total coral cover from Round 1 made up of live coral and recently dead coral lightly covered in algae) and live coral cover as at late 2016 (from Round 2), relative to the pre-bleach coral cover.

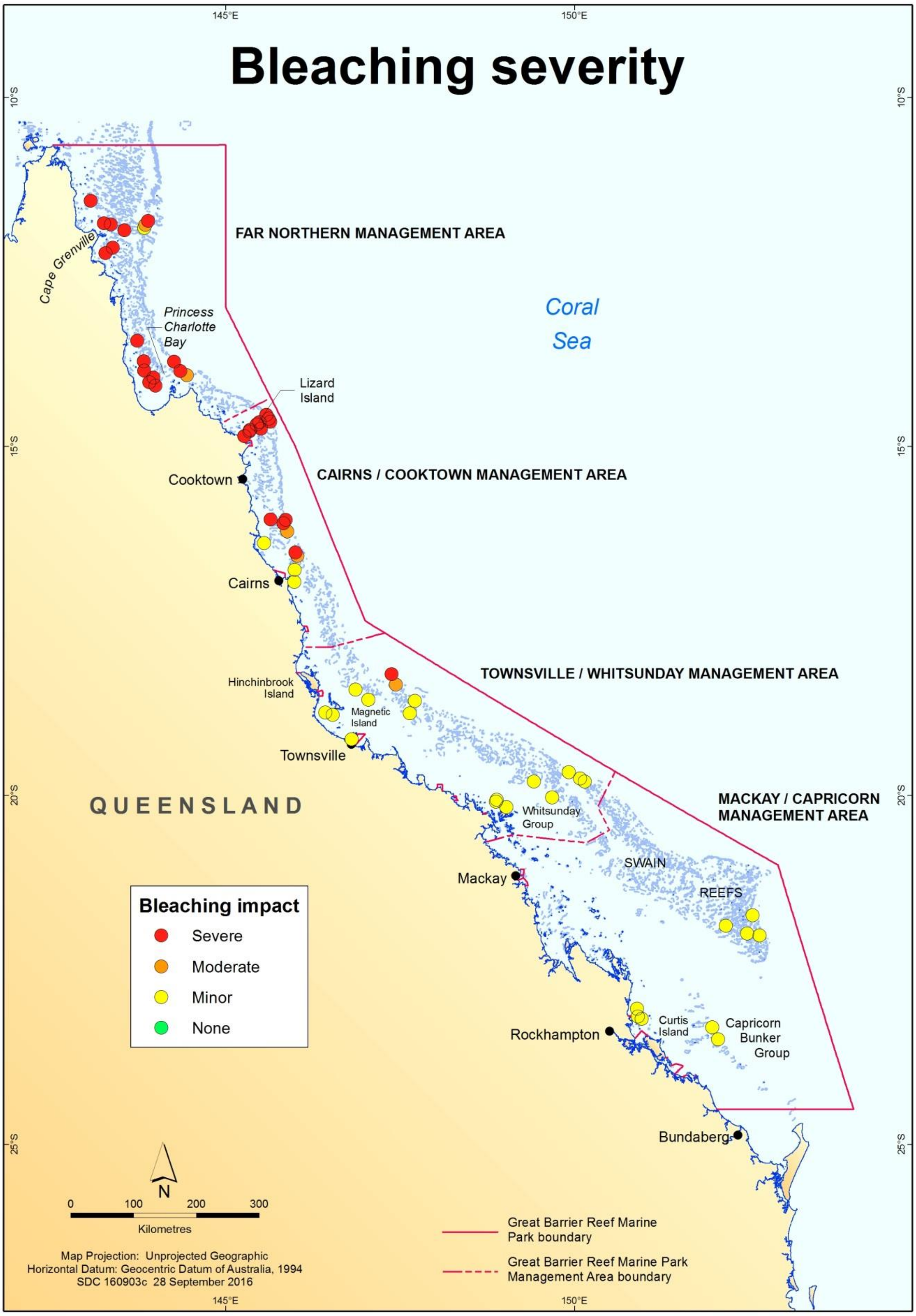

Figure 5 Reef-wide pattern of bleaching severity impacts on the Great Barrier Reef in 2016 on 62 reefs surveyed using the RHIS method. Each circle represents a survey reef and colours indicate severity category, with red indicating the most severely impacted reefs. See Appendix B for descriptions. Data are from Round 1 reef health and impact surveys (March to June 2016).

A latitudinal gradient of bleaching severity was observed — with more severe bleaching on reefs within the three northern-most transects, and impacts generally decreasing southward (Figure 6). The Cairns–Port Douglas area exhibited the highest variability in bleaching patterns across reefs, with a mix of minor, moderate and severely bleached reefs. Supplementary reef health and impact surveys confirmed this pattern of bleaching[†††]. Only one surveyed reef (Myrmidon Reef) was categorised as severely bleached on the Townsville transect. Reefs in the Whitsunday transect experienced only minor bleaching. Although some severe bleaching was observed at some sites within reefs in the Rockhampton transect, the overall impact of bleaching was minor on all reefs in this transect. All survey reefs had some level of bleaching, consistent with a Reef-wide mass bleaching event.

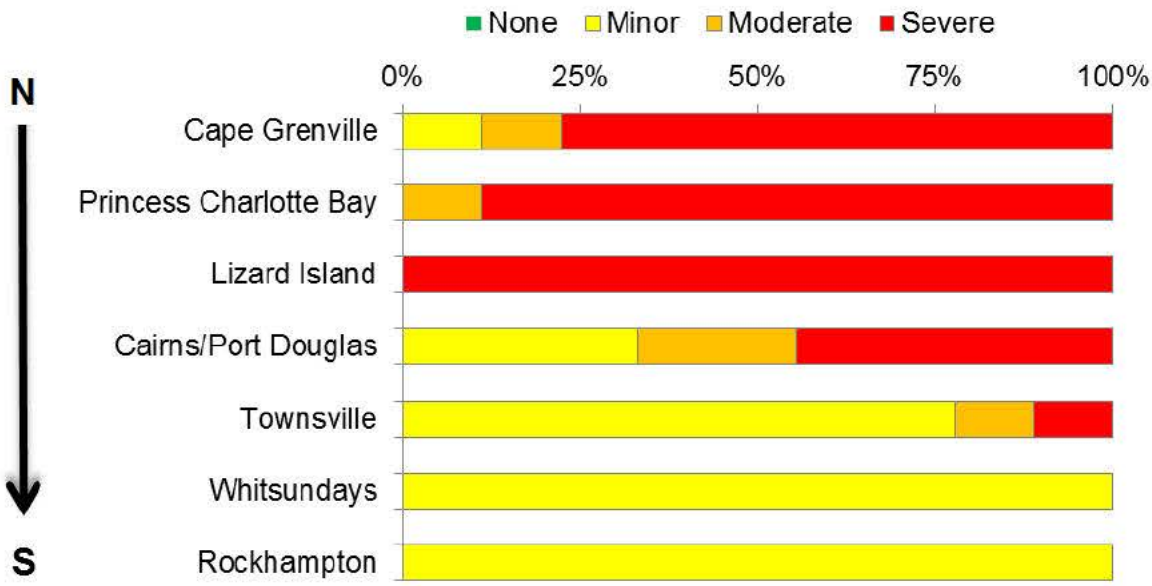

Figure 6 Illustration of the proportion of reefs within each transect that exhibited either no, minor, moderate or severe bleaching. Data are from Round 1 RHIS surveys of 62 reefs.

The high variability in bleaching severity during the peak of the event is best illustrated by analysis at the survey level. Of all Round 1 reef health and impact surveys, bleaching was observed in 92.1 per cent. Most of the 873 Round 1 surveys at transect reefs analysed in this report recorded minor bleaching impact (48.6 per cent), followed by 33.2 per cent of surveys with an overall severe bleaching impact. In 10.3 per cent of surveys moderate bleaching impacts were recorded. Only 7.9 per cent of all Round 1 surveys showed no bleaching. Of Round 1 surveys with bleaching present, there was a high variability in the proportion of coral bleached, ranging from 0.2 per cent of coral cover to 100 per cent.

[†††] Additional information on bleaching severity and mortality was available for six additional reefs (Moore Reef, Vlasoff Reef, Agincourt Reefs (No3), Chinaman Reef, Parkinson Reef and Outer Reef) surveyed opportunistically by GBRMPA at the same times as the Round 1 and Round 2 surveys. Bleaching severity information was also examined for a further 61 reefs from supplementary surveys and anecdotal reports where there was sufficient information provided through the Eye on the Reef monitoring network. These data provided greater spatial coverage, particularly in the Port Douglas to Townsville area, and confirmed bleaching patterns described in this report.

Across the entire Reef, severe bleaching did not follow a strong pattern with regards to shelf position. Of the 290 Round 1 surveys that recorded severe bleaching impacts, 35.5 per cent were located on inshore reefs, 39 per cent on mid-shelf reefs and 25.5 per cent on outer shelf reefs.

However, latitudinally (by transect), severe bleaching was highly variable amongst shelf positions (Figure 7a, b, c). Although the two northern-most transects had severe bleaching in all shelf positions, most of the severe bleaching occurred on the inshore and mid-shelf reefs. In the Lizard Island region, severe bleaching occurred at all shelf positions. For the Cairns–Port Douglas transects, the most severe bleaching occurred on the mid and outer shelf reefs, whereas the Townsville transect had the most severe bleaching on outer shelf reefs. In the two southern-most transects, the Whitsundays reefs did not exhibit any severe bleaching, while the Rockhampton transect only exhibited severe bleaching on some inshore reef surveys (Figure 7a, b, c).

Only minor impacts were recorded from non-bleaching impacts (i.e. coral disease, predation by crown-of-thorns starfish (*Acanthaster planci*) and snails (*Drupella* spp.), and recent damage) on the 62 surveyed reefs in 2016. The non-bleaching impacts only affected a very low percentage of coral cover (less than 1 per cent on average) during Round 1 surveys.

Even on individual reefs, large variations in bleaching severity were observed, as illustrated by plotting bleaching severity impacts from individual surveys on a reef outline (Figure 8a, b, c). As replicate RHIS surveys within a particular aspect of the reef (for example, north-east) were only 50 metres apart, the severity of bleaching within a small area differed greatly (Figure 8a, b, c). On all but the most severely impacted reefs, patches of unbleached coral cover were often found adjacent to completely bleached corals. Bleaching was observed at all surveyed depths (Figure 8b) in this example (as was generally the case), and depth did not appear to be a factor in bleaching severity. Direct observations of bleaching down to 25 metres were noted on several reefs (but beyond the areas surveyed).

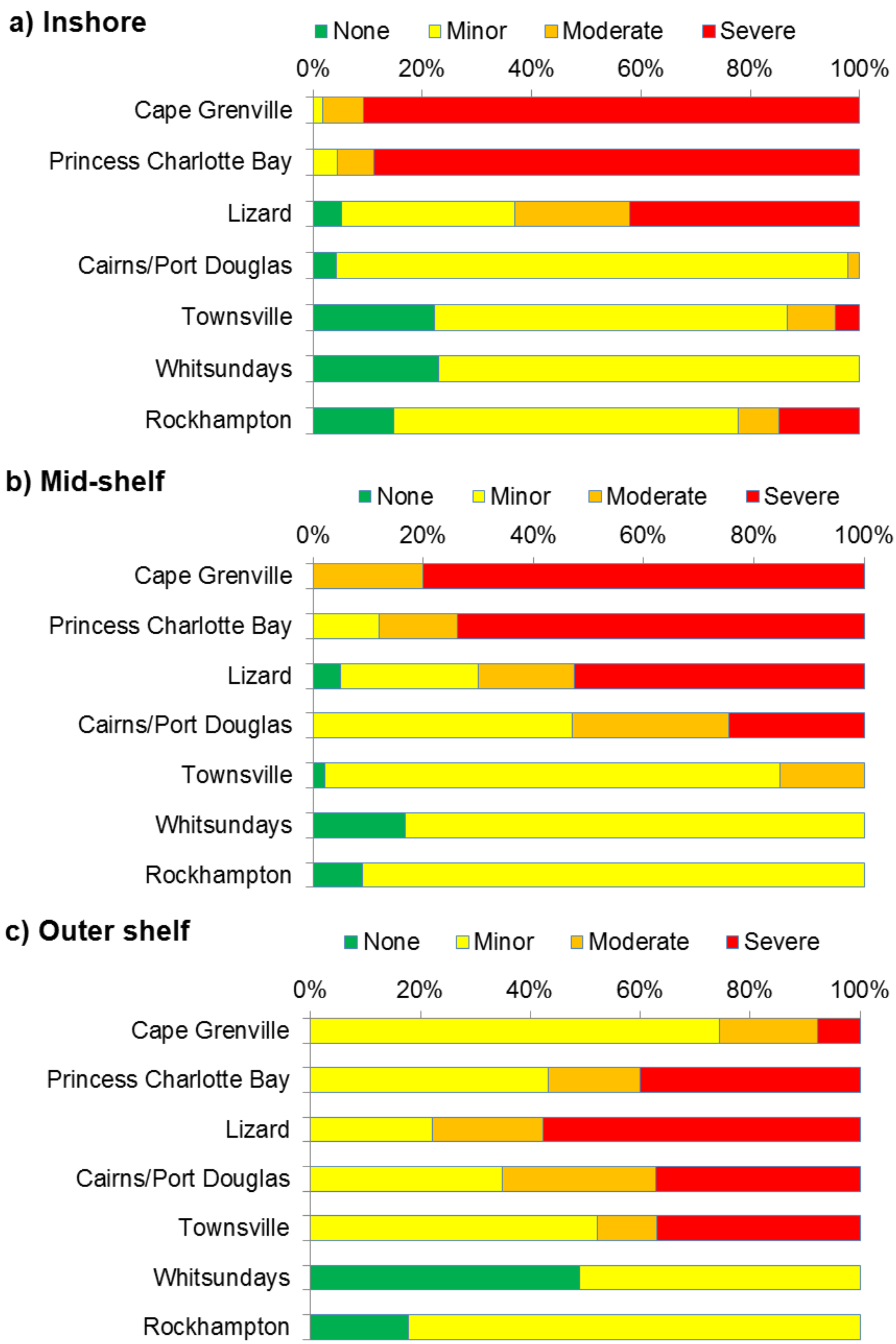

Figure 7a,b,c Illustration of bleaching severity impacts during the peak of the event as a proportion of the total surveys conducted on a) inner shelf reefs, b) mid-shelf reefs and c) outer shelf reefs of each transect along the Great Barrier Reef. Data are from Round 1 RHIS surveys (March to June 2016).

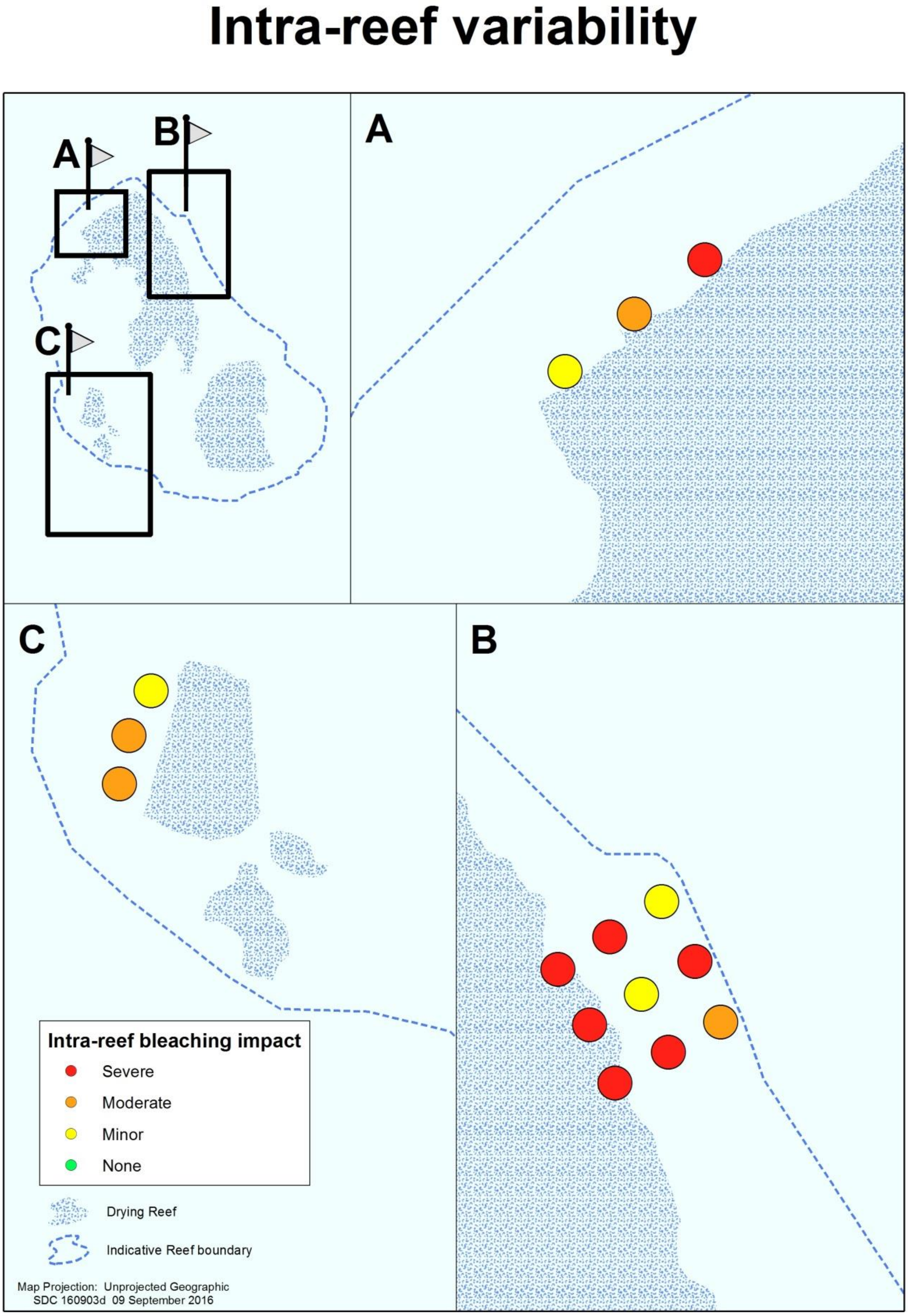

Figure 8a,b,c Illustration of bleaching variability within a reef.

Bleaching severity impacts recorded on individual RHIS surveys 50 metres apart on three different reef aspects and depths: a) one depth on the north-west aspect, b) three depths on the north-east aspect and c) one depth on the south-west aspect. In this example, based on actual survey data, bleaching severity within a reef varied from minor to severe.

Scale and spatial patterns of coral mortality (as at 3 June 2016)
Reef-wide coral bleaching caused substantial die-off of corals by early June and patterns of mortality also exhibited a north-south gradient, with high variability across locations (Figure 9). The proportion of coral in Round 1 surveys that had recently died due to severe bleaching ranged from zero to 100 per cent of total coral cover in individual RHIS surveys, and many areas escaped with little or no bleaching mortality. Some reefs off the Cape Grenville and Princess Charlotte Bay transects had very high bleaching mortality, losing over 50 per cent of their coral cover, whereas reefs in the south had little to no coral mortality from bleaching. The proportion of coral that died on each reef was associated with bleaching severity — the highest levels of mortality were observed in areas with the highest bleaching severity (estimated based on the RHIS surveys, Figure 5) and the most accumulated heat stress (Figure 4).

The agency's preliminary findings indicated 22 per cent of coral on the Reef had died due to severe bleaching by early June 2016.[45] This was for shallow-water corals (less than approximately 10 metres depth), which are the most diverse and productive corals, and provide the key reef habitat important for Reef users (e.g. tourism). Eighty-five per cent of this mortality occurred in the 600 kilometre stretch between the tip of Cape York and just north of Lizard Island. At reefs around Lizard Island, Round 1 surveys were conducted before the peak of bleaching and initial mortality, and further mortality was reported during June 2016 (i.e. still during the Round 1 survey period). Therefore, estimates for reefs in that transect area[‡‡‡] in particular were anticipated to underestimate mortality to June 2016.

The level of bleaching-related mortality differed depending on shelf-position. Of all surveys that recorded coral mortality, the greatest proportion of die-off was on mid-shelf reefs (47 per cent of all surveys), then inshore reefs (32 per cent of surveys), with the least coral mortality observed on outer shelf reefs (21 per cent).

Eye on the Reef reports of bleaching and coral mortality continued into the 2016 Austral winter (i.e. mid-year).

Scale and spatial patterns of coral mortality (as at November 2016)
Bleaching-related mortality had increased by the time the Round 2 surveys in late 2016 were conducted, approximately six-months after peak bleaching, again exhibiting a north-south gradient with high variability across locations (Figure 10).

Between June and November 2016, the proportion of the 62 surveyed reefs that had lost more than half of their coral cover (i.e. with 50 per cent or greater bleaching-related mortality) increased from 10 per cent to just under 30 per cent. Mortality increased substantially in areas that experienced the most severe bleaching — with extreme mortality (more than 75 per cent) of shallow-water corals in 16 per cent of surveyed reefs reported here.

[‡‡‡] The Lizard Island region only accounted for a small proportion of the Marine Park's pre-bleaching coral cover (due to its history of disturbances including two recent severe cyclones and the available area of reef habitat). Therefore, the overall coral loss figure is not strongly influenced by results for that area.

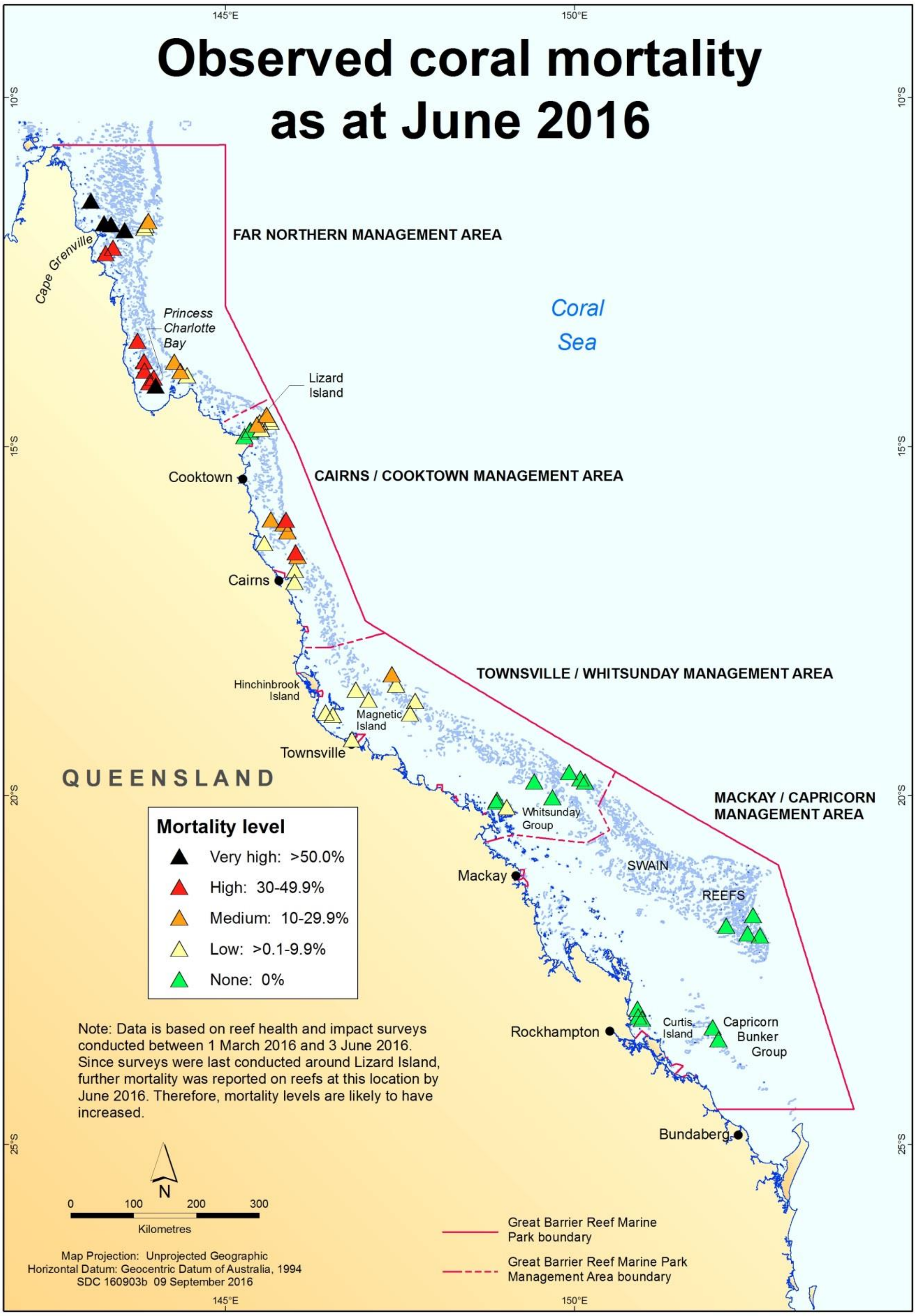

Figure 9 Reef-wide pattern of observed recent coral mortality due to coral bleaching as at June 2016 on the Great Barrier Reef.

Each triangle represents a reef, and colours indicate the percentage of coral cover that died (mortality level). Black triangles indicate reefs with greater than 50 per cent coral loss due to severe bleaching.

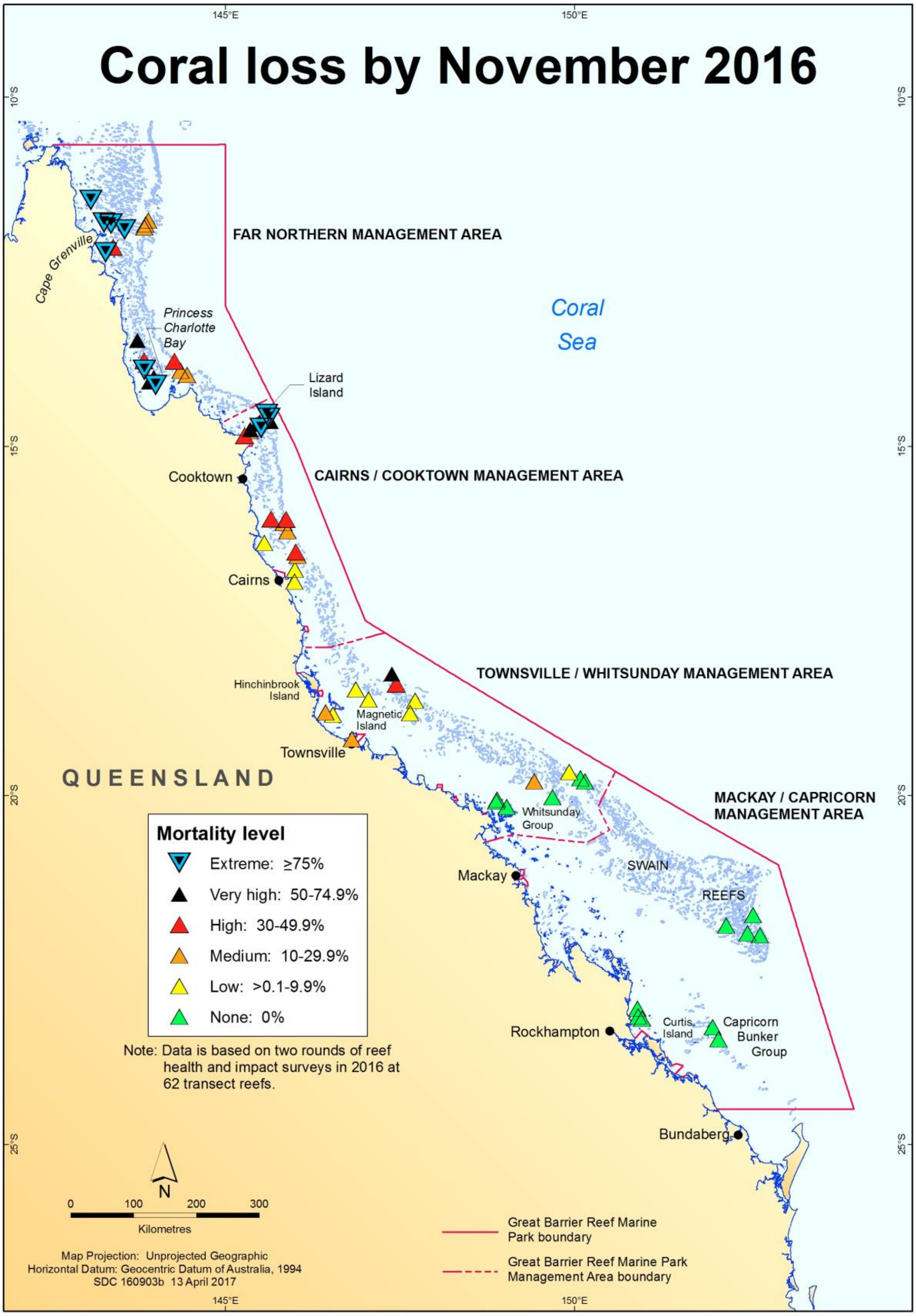

Figure 10 Reef-wide pattern of estimated coral loss (proxy for coral mortality) as at November 2016 on the Great Barrier Reef.

Each triangle represents a reef, and colours indicate the percentage of coral cover that died (mortality level). Blue triangles indicate reefs with extreme mortality (greater than 75 per cent coral loss due to severe bleaching).

At the worst affected sites (e.g. on reefs with very high or extreme levels of bleaching-related mortality), few if any hard or soft corals without visible impacts remained, and up to 100 per cent of the coral cover had died from bleaching. Extensive algal overgrowth was observed on some reefs.

Coral mortality increased during 2016, with an increase from the June 2016 estimate of 22 per cent to an estimated 29 per cent loss of shallow-water corals on the Great Barrier Reef by November 2016 due to the worst mass bleaching event on record. Over seventy five per cent of all the bleaching-related mortality in 2016 occurred in the far north — the 600 kilometre stretch between the tip of Cape York and just north of Lizard Island. Overall, the southern Great Barrier Reef did not exhibit significant bleaching-related mortality (or other major reef health impacts) in 2016, consistent with the lower exposure to heat stress (Figure 4) in that area.

Early signs of recovery (such as coral colonies regaining their normal colour) were observed during 2016, particularly during the second half of the year in areas where bleaching had been less severe. However, in late 2016 some live coral colonies were still visibly fully-bleached, or had partial colony mortality, indicating ongoing bleaching impacts.

Spatial patterns of remaining coral cover (as at November 2016)

Round 1 surveys provided total coral cover estimates for early 2016 (i.e. immediately prior to the onset of mass coral bleaching in 2016,) using summed live coral cover and recently dead coral cover estimates from that round of RHIS surveys. This showed that coral cover was variable, but most surveyed reefs still had moderate to high coral cover (Figure 11).

Despite coral losses due predominantly to coral bleaching, many surveyed reefs still had relatively high coral cover (42 per cent or more of hard and soft coral cover) in late 2016 (i.e. when each reef was last assessed between September and November 2016). However, there was high variation in coral cover across the Marine Park, and by late 2016 some surveyed reefs and the whole Lizard region now had very low coral cover (well under 10 per cent). These patterns (Figure 12) varied in relation to the coral cover immediately prior to bleaching (Figure 11), and the scale and spatial patterns of coral mortality described above.

(See the separate report by GBRMPA for information on ongoing bleaching and other Reef health disturbances affecting coral cover in 2017, available at www.gbrmpa.gov.au).

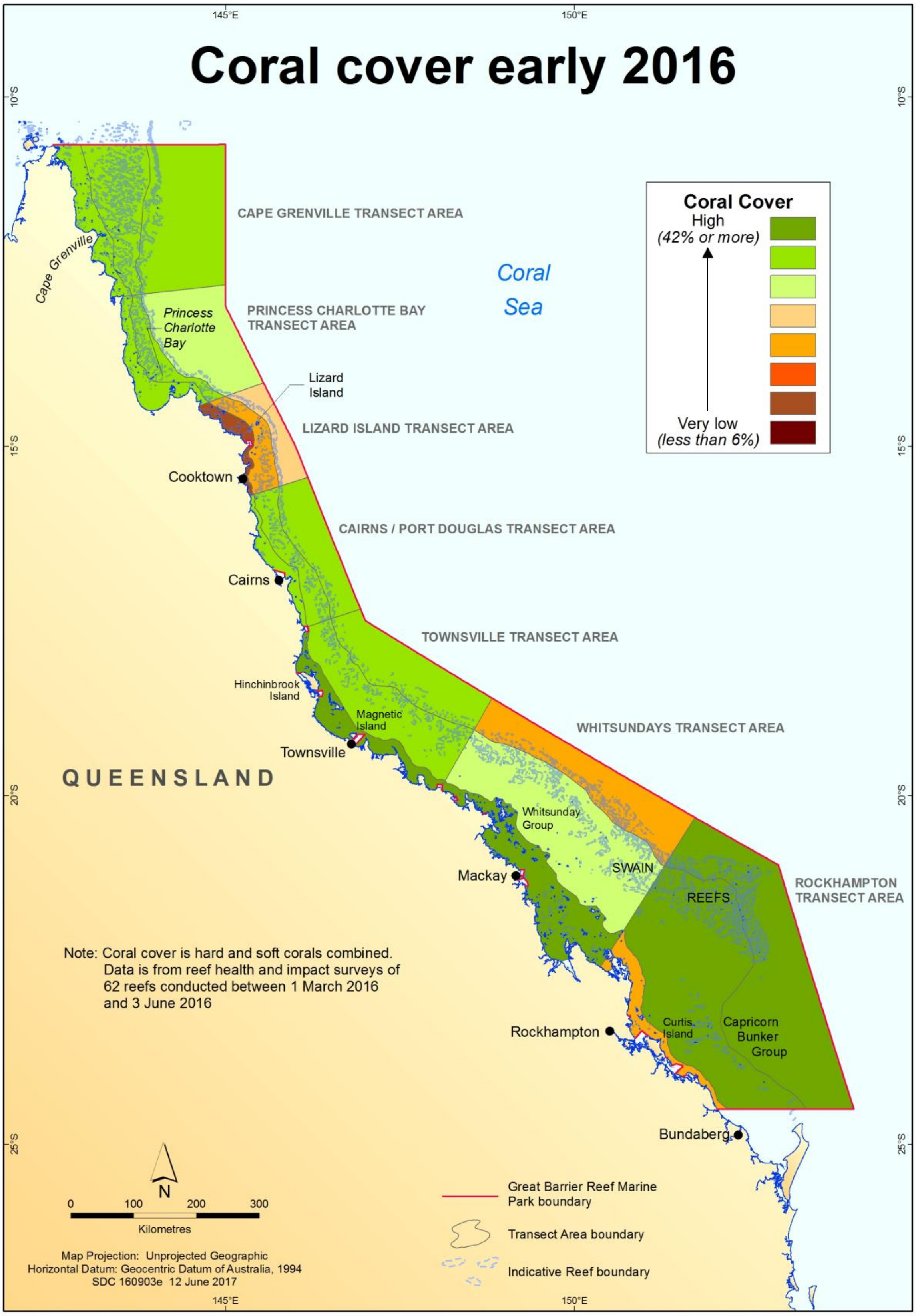

Figure 11 Estimated coral cover as at early 2016 on the Great Barrier Reef.

The colour scale represents indicative coral cover (from high to very low) using estimated averages (means) for surveyed reefs

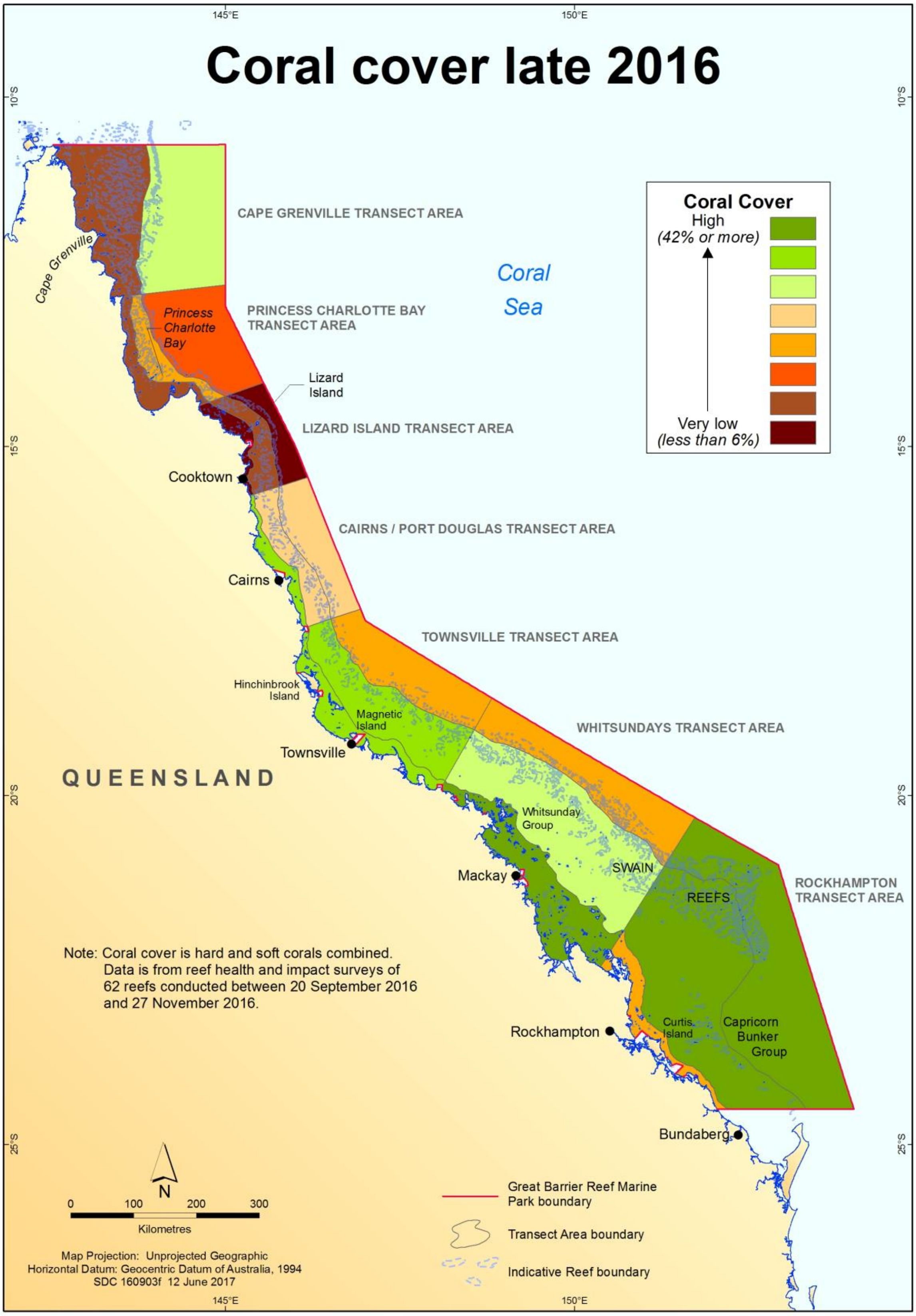

Figure 12 Estimated coral cover as at late 2016 on the Great Barrier Reef.

The colour scale represents indicative coral cover (from high to very low) using estimated averages (means) for surveyed reefs.

CONCLUSIONS AND OUTLOOK FOR RECOVERY

Since 2014 there has been a global mass coral bleaching due to record-breaking temperatures, resulting in the most severe and widespread coral bleaching event recorded on the Great Barrier Reef in 2016. The impacts are ongoing.

Underwater surveys documented widespread bleaching of varying levels of severity throughout the Reef, with the most severe bleaching occurring north of Port Douglas. The results are consistent with other published findings.[31,49,50] A second round of surveys in late 2016 updated preliminary estimates of bleaching-related mortality. As at November 2016, estimates based on surveys of 62 reefs indicated that prolonged heat stress driven by climate change resulted in the loss of an average of 29 per cent of shallow-water coral on the Great Barrier Reef in 2016. The highest coral mortality and associated reef habitat loss was on inshore and mid-shelf reefs around Cape Grenville and Princess Charlotte Bay, in the far north.

The reef health and impact surveys recorded minor non-bleaching impacts from coral disease, predation and recent damage on the 62 surveyed reefs in 2016. However, those impacts only affected a very low percentage of coral cover (less than 1 per cent on average), so by far the major impact in this period was coral bleaching. Coral bleaching did extend beyond depths divers typically survey to, but mortality cannot be systematically estimated for deeper corals due to lack of data, and their role in reef recovery is unknown.

Variability in bleaching severity and coral mortality was greatest among reefs in the Cairns–Port Douglas areas. Most reefs in the southern half of the Marine Park did not have major impacts from bleaching. As at November 2016 early signs of coral recovery had been observed on parts of the Reef. At the end of 2016, remaining coral cover (of hard and soft corals combined) varied across the Marine Park from very low (6 per cent or less) to high (42 per cent or more).

The second consecutive year of mass coral bleaching on the Great Barrier Reef in 2017 is causing further substantial coral loss. This adds to the impacts reported here, since the Reef has not had enough time for recovery between these disturbances. Coral disease has increased and is considered to be a consequence of the heat stress. Other simultaneous impacts (including from crown-of-thorns starfish outbreaks and severe tropical cyclone Debbie in March 2017) are also affecting the Reef, as summarised in a 2017 report by GBRMPA, further reducing coral cover.

A bleached reef can recover in two ways: its surviving corals recover from bleaching by regaining their symbiotic algae and continue to grow, and/or successful coral recruitment replenishes the reef with juvenile corals which, if no further stress is experienced, will grow to eventually take the place of corals that died in this event.[5,13] In ideal circumstances, bleached corals can regain their colour within a period of weeks to months once water temperatures return to normal.[52]

Even if a coral regains its symbionts and hence colour, this does not necessarily mean it is in good health. Research shows bleaching can deplete the corals' energy and prevent it from reproducing for one or two years.[5,22,23] Corals can also grow slower and have lower calcification rates for up to eight years[24,25], and are more vulnerable to coral diseases[26,27]. Ultimately, therefore, bleaching has acute and chronic impacts on corals, and recovery of coral cover may be slower than following some other types of disturbances.[24,53]

Bleaching-related coral mortality has flow-on effects for reef-associated species. Many coral reef fishes and invertebrates rely on live, healthy coral for their survival, and so are particularly vulnerable to impacts from this event.[6,7,54] Given the unprecedented scale and nature of the bleaching, reef resilience overall may have been reduced. It is too early to estimate how many years it will take for coral reefs to recover from this period of extreme heat stress. This is especially the case for the Far Northern Great Barrier Reef (north of Lizard Island), as these reefs are poorly studied and have had few major disturbances since long-term monitoring began in 1985.

The severity of this bleaching event reinforces the urgent need for the strongest possible global action on climate change, and strong local action to improve the resilience of the Reef ecosystem.[31,55] From a coral reefs perspective, it is critical to limit global temperature rise to no more than 1.5 degrees Celsius above pre-industrial levels, and preferably less (noting average global temperatures are already approaching 1 degree Celsius).[56,57,58] This requires much greater emissions reduction efforts globally than currently pledged by nations around the world.

The Great Barrier Reef has previously demonstrated the ability to recover from past disturbances, including mass bleaching events.[59,60,61] However, bleaching events are expected to increase in frequency and severity as a result of climate change, making recovery processes increasingly important for reefs to persist as coral-dominated systems.[32,62] Significantly, many human activities adversely affect the Reef — compounding the risks imposed by coral bleaching and potentially lengthening recovery timeframes.[63,64] For example, chronic stress due to poor water quality can affect the recovery potential of reef communities because reproduction and larval recruitment in corals are particularly sensitive to environmental conditions.[65,66,67] Reducing compounding stressors will help reefs cope with or recover from coral bleaching events, which will in turn build the resilience of reefs to future climate-related disturbances, but only to a point. Further loss of coral as global warming continues is inevitable and can be minimised rather than prevented if the aspirational goal of the 2015 Paris Agreement is reached.

Assessing reef condition and impacts ensures GBRMPA has an up-to-date understanding of Reef health, including the acute and chronic effects of heat stress. It also assists in targeting resilience-building management strategies and raising awareness (for example, communicating the importance of protecting herbivorous reef fishes to support recovery processes on coral reefs). Event-based impact assessments (such as this one) are underpinned by an integrated monitoring and reporting program, which includes long-term monitoring of coral cover by AIMS since 1985. This provides a holistic picture of trends in coral cover, including both coral losses from impacts and coral growth from recovery, allowing disturbance events to be viewed in a historical context.

The agency is also working with researchers to rapidly advance its understanding of factors which increase the resilience of reefs, as measured by the capacity to resist, tolerate and recover from disturbances. It is also increasing its understanding of spatial variability in the likelihood a site will be impacted by disturbances such as bleaching, disease outbreaks, floods and cyclones based on location, coral community composition and thermal history. Greater knowledge of how spatial variability contributes to reef resilience is essential to inform resilience-based management. This also enables assessments of the effectiveness of strategies implemented to support resilience.

The bleaching highlights the importance of GBRMPA's strong measures in place to protect biodiversity, including no-take green zones which make up 33 per cent of the Marine Park. These no-take reefs may have higher recovery potential and greater resistance to moderate disturbances.[61,61,61,68] Practical conservation actions for species and habitats are also undertaken to support ecosystem resilience. In addition, the agency is working with partners to explore active restoration approaches, which may in the longer-term confer some local benefits to reefs.

Through the Australian and Queensland governments' Reef 2050 Long-Term Sustainability Plan, significant investment is being made to restore the integrity of Reef catchments and improve water quality entering the Reef. This is in addition to work that has been taking place since 2003 to reduce nutrients, pesticides and sediments in farm run-off. Considerable efforts are also being made under the plan to reduce the impacts of other pressures to help reefs cope with or recover from disturbances.

In addition to measures aimed at building ecosystem resilience, partnerships with a broad range of stakeholders can help build social and economic resilience to coral bleaching events. GBRMPA is partnering with Reef users to ensure they are well-informed of risks and are included in management and contingency planning to help them cope and adapt to reef health incidents. Similarly, stewardship activities such as the Reef Guardian program are encouraging responsible reef practices, such as not anchoring on corals or disposing of fishing tackle on the Reef.

While these actions to reduce pressures and build resilience remain crucial, environmental management efforts can only compensate for reduced coral reef resilience in the face of climate change to a limited extent and over a limited timeframe.[69]

The Great Barrier Reef Outlook Report 2014[64] found the overall outlook for the Reef ecosystem is poor and worsening. This assessment was reached after taking into account 150 years of past and accumulating human-caused impacts such as poor water quality and crown of thorns starfish outbreaks, and then secondly taking into account the very poor forward outlook for the reef under climate change driven by the enhanced greenhouse effect.

Unprecedented mass coral bleaching occurring in successive years, in 2016 and 2017, has hastened the decline. As an agency tasked with managing and protecting the Reef for current and future generations, GBRMPA remains extremely concerned about the current and future very destructive impacts of climate change on the Great Barrier Reef Marine Park and World Heritage Area. We are keenly aware that mitigating global climate change remains the most difficult policy challenge to secure the long-term future of the Great Barrier Reef, and other coral reef ecosystems worldwide.

ACKNOWLEDGEMENTS

The Great Barrier Reef Marine Park Authority (GBRMPA) thanks peer-reviewers for constructive feedback that improved this report. GBRMPA also acknowledges and thanks its partners, stakeholders and staff who participated in the coral bleaching incident response in 2016. Understanding how coral bleaching impacted the Marine Park — an area bigger than Italy — benefits from a network of science, tourism and reef partners assisting us in our efforts.

The first round of field assessments under the agency's incident response was mainly resourced through the Field Management Program, jointly funded by the Australian and Queensland governments. Program staff, the incident management team, and the agency's spatial data centre contributed to this work, along with many other agency teams. The second round of surveys and associated resilience assessment received financial support from the Great Barrier Reef Foundation, and additional resourcing from the Field Management Program. The agency's Reef Recovery section led the forward-planning and environmental assessment.

The GBRMPA Eye on the Reef program provided the monitoring network and reporting system that underpinned this assessment. We thank everyone who contributes to this important monitoring effort. Further details on the program are available on our website. The Reef health early warning system uses tools and services provided by the Australian Bureau of Meteorology, the United States National Oceanic and Atmospheric Administration and several other organisations. For details, see GBRMPA's Coral Bleaching Risk and Impact Assessment Plan.

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The bleaching impact assessment has been conducted in collaboration with the Queensland Parks and Wildlife Service, and many other partners including the Bureau of Meteorology, National Oceanic and Atmospheric Administration, Australian Institute of Marine Science, Australian Research Council Centre of Excellence for Coral Reef Studies, and the National Coral Bleaching Taskforce (instigated by Prof Terry Hughes, Centre of Excellence).

The information in this report is focused on the Great Barrier Reef. We recognise the global coral bleaching event is ongoing, and has affected and is continuing to affect other parts of Australia and the world.

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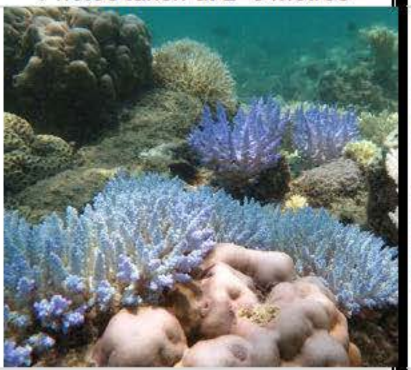
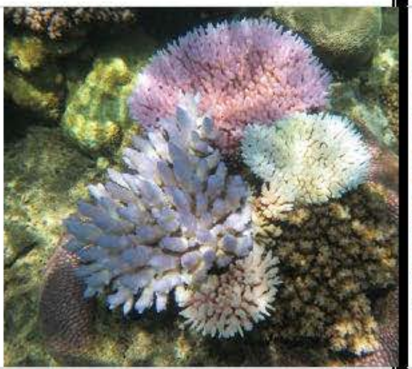
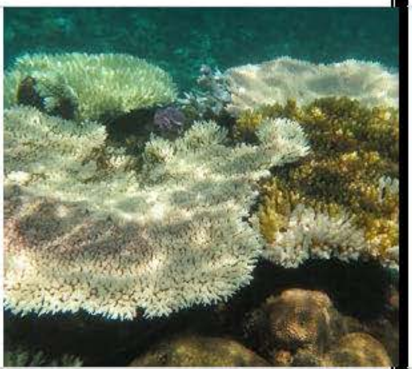
APPENDIX A: List of reefs surveyed in each cross-shelf transect.

Official reef identification numbers are provided for each reef, and the first two digits represent the latitude of the reef. The Great Barrier Reef Marine Park is divided into four Management Areas, and the table shows which transects are in each of these.

Transect	Inshore	Mid-shelf	Outer shelf
Far Northern Management Area			
Cape Grenville	U/N Reef (11–060) Nomad Reef (12–007) Kay Reef (12–010)	Guthray Reef (11–171) Cockburn Reef (11–173) Sir Charles Hardy Islands Reef (11–184c)	Three Reefs (11–223) Devlin Reef (11–229a) Five Reefs (11–232)
Princess Charlotte Bay	Pelican Island Reef (13–107) Eden Reef (14–008) Wharton Reef (14–022)	Morris Island Reef (13–072) Magpie Reef (13–087) Grub Reef (14–003)	U/N Reef (13–121) Rodda Reef (13–127) Davie Reef (13–130)
Cairns–Cooktown Management Area			
Lizard Island	Martin Reef (14–123) Linnet Reef (14–126) Decapolis Reef (14–131)	MacGillivray Reef (14–114) Lizard Island Reef (Lagoon) (14–116d) North Direction Reef (14–143)	Carter Reef (14–137) Yonge Reef (14–138) No Name Reef (14–139)
Cairns–Port Douglas	Low Islands Reef (16–028) Green Island Reef (16–049) Fitzroy Island Reef (16–054a&f)	Mackay Reef (16–015) Hastings Reef (16–057) Michaelmas Reef (16–060)	Agincourt Reefs (No. 1) (15-099c) St Crispin Reef (16–019) Opal Reef (16–025)
Townsville–Whitsundays Management Area			
Townsville	Pandora Reef (18-051) Havannah Reef (18-065) Middle Reef (19-011)	Rib Reef (18–032) John Brewer Reef (18–075) Davies Reef (18-096)	Myrmidon Reef (18–034) Dip Reef (18–039) Chicken Reef (18–086)
Whitsundays	Hayman Island Reef (20–014) Langford-Bird Reef (20–019) Border Island Reef (No.1) (20–067a)	U/N Reef (19–138) U/N Reef (20–104)	Slate Reef (19–159) Hyde Reef (19–207) Rebe Reef (19–209)
Mackay–Capricorn Management Area			
Rockhampton	North Keppel (Ko-no-mie) Island Reef (No. 1) (23–004a) Middle (Ba-la-ba) Island Reef (23–010) Halfway Island Reef (23–014)	U/N Reef (21–529) Wreck Island Reef (23–051) One Tree Island Reef (23–055a)	Gannett Cay Reef (21–556) Turner Reef (21–562) Chinaman Reef (22–102)

APPENDIX B: Example illustrations and descriptions

Below are examples of coral bleaching impact severity levels used to assess reef health. Factors that differ among severity levels are: types of coral, bleaching severity, depth and number affected (Coral Bleaching Risk and Impact Assessment Plan 2013).

<table>
<tr><th>Minor</th><th>Moderate</th><th>Severe</th></tr>
<tr><td>Photos taken at 2–3 metres</td><td>Photos taken at 3–6 metres</td><td>Photos taken at >9 metres</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td></tr>
<tr>
<td>
Bleaching mainly confined to reef flat
Severe bleaching of many (10–50 per cent) colonies of taxa (Acropora and Pocillopora), or morphologies (branching, bushy, tabular/plate) usually highly sensitive to bleaching)
Severe bleaching of some (<10 per cent) colonies of taxa (Montipora and Faviids) or morphologies with low sensitivity to bleaching (encrusting and mushroom)
Paling of colonies of taxa (Porites) or morphologies (massives) with very low sensitivity to bleaching
Severe bleaching of colonies of taxa or morphologies with low or very low sensitivity to bleaching but confined to reef flat.
</td>
<td>
Mortality confined to reef flat; bleaching extends deeper than reef flat
Severe bleaching of most (>50 per cent) colonies of taxa or morphologies usually highly sensitive to bleaching
Severe bleaching of many (10–50 per cent) colonies of taxa or morphologies with low sensitivity to bleaching below reef crest
Severe bleaching of some (<10 per cent) colonies of taxa or morphologies with very low sensitivity to bleaching
Some mortality of colonies of taxa or morphologies usually highly sensitive to bleaching but confined
</td>
<td>
Bleaching extends deeper than upper reef slope
Mortality of many (>50 per cent) colonies of taxa or morphologies usually highly sensitive to bleaching
Severe bleaching of most (>50 per cent) colonies of taxa or morphologies with low sensitivity to bleaching
Severe bleaching of many (10–50 per cent) colonies of taxa or morphologies with very low sensitivity to bleaching.
</td>
</tr>
</table>

APPENDIX C: Time-series images

Below are time-series images taken at a patch of coral reef over 10 months, illustrating the impacts of bleaching over time. Red stars indicate areas of coral that died due to severe coral bleaching and the two yellow stars on the third photograph indicate crown-of-thorns starfish feeding scars:

a) healthy coral on a reef flat in October 2015

b) In April 2016, about half of the coral had died from bleaching with the other half, predominantly in the centre of the image still bleached.

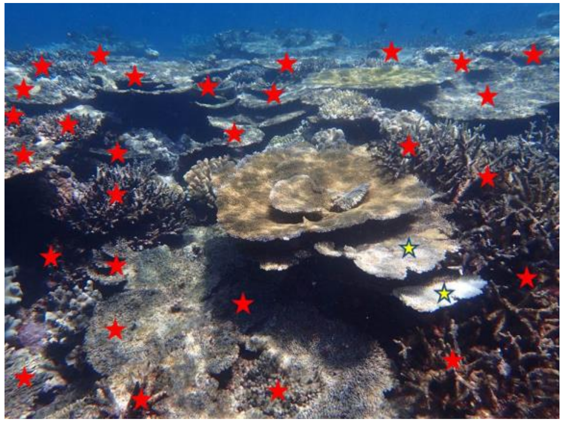
c) In September 2016, surviving coral colonies in the centre of the image show signs of recovery (regained their natural brown colour) after the peak of the bleaching event, amid very high mortality (>50 per cent) of surrounding colonies .

The bleaching susceptibility of an area of reef will be influenced by the community composition since different coral tax have different bleaching susceptibility, among other factors.

(Photos: ©Taylor Simpkins 2016)

a) 

b) 

c) 

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Global warming and recurrent mass bleaching of corals

Terry P. Hughes[1], James T. Kerry[1], Mariana Álvarez-Noriega[1,2], Jorge G. Álvarez-Romero[1], Kristen D. Anderson[1], Andrew H. Baird[1], Russell C. Babcock[3], Maria Beger[4], David R. Bellwood[1,2], Ray Berkelmans[5], Tom C. Bridge[1,6], Ian R. Butler[7], Maria Byrne[8], Neal E. Cantin[9], Steeve Comeau[10], Sean R. Connolly[1,2], Graeme S. Cumming[1], Steven J. Dalton[11], Guillermo Diaz-Pulido[12], C. Mark Eakin[13], Will F. Figueira[14], James P. Gilmour[15], Hugo B. Harrison[1], Scott F. Heron[13,16,17], Andrew S. Hoey[1], Jean-Paul A. Hobbs[18], Mia O. Hoogenboom[1,2], Emma V. Kennedy[12], Chao-yang Kuo[1], Janice M. Lough[1,9], Ryan J. Lowe[10], Gang Liu[13,16], Malcolm T. McCulloch[10], Hamish A. Malcolm[11], Michael J. McWilliam[1], John M. Pandolfi[7], Rachel J. Pears[19], Morgan S. Pratchett[1], Verena Schoepf[10], Tristan Simpson[20], William J. Skirving[13,16], Brigitte Sommer[7], Gergely Torda[1,9], David R. Wachenfeld[19], Bette L. Willis[1,2] & Shaun K. Wilson[21]

During 2015–2016, record temperatures triggered a pan-tropical episode of coral bleaching, the third global-scale event since mass bleaching was first documented in the 1980s. Here we examine how and why the severity of recurrent major bleaching events has varied at multiple scales, using aerial and underwater surveys of Australian reefs combined with satellite-derived sea surface temperatures. The distinctive geographic footprints of recurrent bleaching on the Great Barrier Reef in 1998, 2002 and 2016 were determined by the spatial pattern of sea temperatures in each year. Water quality and fishing pressure had minimal effect on the unprecedented bleaching in 2016, suggesting that local protection of reefs affords little or no resistance to extreme heat. Similarly, past exposure to bleaching in 1998 and 2002 did not lessen the severity of bleaching in 2016. Consequently, immediate global action to curb future warming is essential to secure a future for coral reefs.

The world's tropical reef ecosystems, and the people who depend on them, are increasingly affected by climate change[1–7]. Since the 1980s, rising sea surface temperatures owing to global warming have triggered unprecedented mass bleaching of corals, including three pan-tropical events in 1998, 2010 and 2015/16 (ref. 1). Thermal stress during marine heatwaves disrupts the symbiotic relationship between corals and their algal symbionts (*Symbiodinium* spp.), causing the corals to lose their colour[2,3]. Bleached corals are physiologically damaged, and prolonged bleaching often leads to high levels of coral mortality[5–8]. Increasingly, individual reefs are experiencing multiple bouts of bleaching, as well as the effects of more chronic local stressors such as pollution and overfishing[1–4]. Our study represents a fundamental shift away from viewing bleaching events as individual disturbances to reefs, by focusing on three recurrent bleachings over the past 18 years along the 2,300 km length of the Great Barrier Reef, as well as the potential influence of water quality and fishing pressure on the severity of bleaching.

The geographic footprints of mass bleaching of corals on the Great Barrier Reef have varied markedly during three major events in 1998, 2002 and 2016 (Fig. 1a). In 1998, bleaching was primarily coastal and most severe in the central and southern regions. In 2002, bleaching was more widespread, and affected offshore reefs in the central region that had escaped in 1998 (ref. 8). In 2016, bleaching was even more extensive and much more severe, especially in the northern regions, and to a lesser extent the central regions, where many coastal, mid-shelf and offshore reefs were affected (Fig. 1a, b). In 2016, the proportion of reefs experiencing extreme bleaching (>60% of corals bleached) was over four times higher compared to 1998 or 2002 (Fig. 1f). Conversely, in 2016, only 8.9% of 1,156 surveyed reefs escaped with no bleaching, compared to 42.4% of 631 reefs in 2002 and 44.7% of 638 in 1998. The cumulative, combined footprint of all three major bleaching events now covers almost the entire Great Barrier Reef Marine Park, with the exception of southern, offshore reefs (Fig. 1d).

Explaining spatial patterns

The severity and distinctive geographic footprints of bleaching in each of the three years can be explained by differences in the magnitude and spatial distribution of sea surface temperature anomalies (Fig. 1a, b and Extended Data Table 1). In each year, 61–63% of reefs experienced four or more degree heating weeks (DHWs; °C-weeks). In 1998, heat stress was relatively constrained, ranging from 1–8 DHWs (Fig. 1c). In 2002, the distribution of DHWs was broader, and 14% of reefs encountered 8–10 DHWs. In 2016, the spectrum of DHWs expanded further still, with 31% of reefs experiencing 8–16 DHWs (Fig. 1c). The largest heat stress occurred in the northern 1,000-km-long section of the Great Barrier

[1]Australian Research Council Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland 4811, Australia. [2]College of Science and Engineering, James Cook University, Townsville, Queensland 4811, Australia. [3]Commonwealth Science and Industry Research Organization, GPO Box 2583 Brisbane, Queensland 4001, Australia. [4]School of Biology, University of Leeds, Leeds LS2 9JT, UK. [5]24 Hanwood Court, Gilston, Queensland 4211, Australia. [6]Queensland Museum, 70-102 Flinders St, Townsville, Queensland 4810, Australia. [7]Australian Research Council, Centre of Excellence for Coral Reef Studies, School of Biological Sciences, University of Queensland, Brisbane, Queensland 4072, Australia. [8]School of Medical Sciences, University of Sydney, Sydney, New South Wales 2006, Australia. [9]Australian Institute of Marine Science, PMB 3, Townsville, Queensland 4810, Australia. [10]Australian Research Council Centre of Excellence in Coral Reef Studies, Oceans Institute and School of Earth and Environment, University of Western Australia, Crawley, Western Australia 6009, Australia. [11]Fisheries Research, Department of Primary Industries, PO Box 4291, Coffs Harbour, New South Wales 2450, Australia. [12]School of Environment, and Australian Rivers Institute, Griffith University, Brisbane, Queensland 4111, Australia. [13]Coral Reef Watch, US National Oceanic and Atmospheric Administration, College Park, Maryland 20740, USA. [14]School of Biological Sciences, University of Sydney, Sydney, New South Wales 2006, Australia. [15]Australian Institute of Marine Science, Indian Oceans Marine Research Centre, University of Western Australia, Crawley, Western Australia 6009, Australia. [16]Global Science & Technology, Inc., Greenbelt, Maryland 20770, USA. [17]Marine Geophysical Laboratory, College of Science, Technology and Engineering, James Cook University, Townsville, Queensland 4811, Australia. [18]Department of Environment and Agriculture, Curtin University, Perth, Western Australia 6845, Australia. [19]Great Barrier Reef Marine Park Authority, PO Box 1379, Townsville, Queensland 4810, Australia. [20]Torres Strait Regional Authority, PO Box 261, Thursday Island, Queensland 4875, Australia. [21]Department of Parks and Wildlife, Kensington, Perth, Western Australia 6151, Australia.

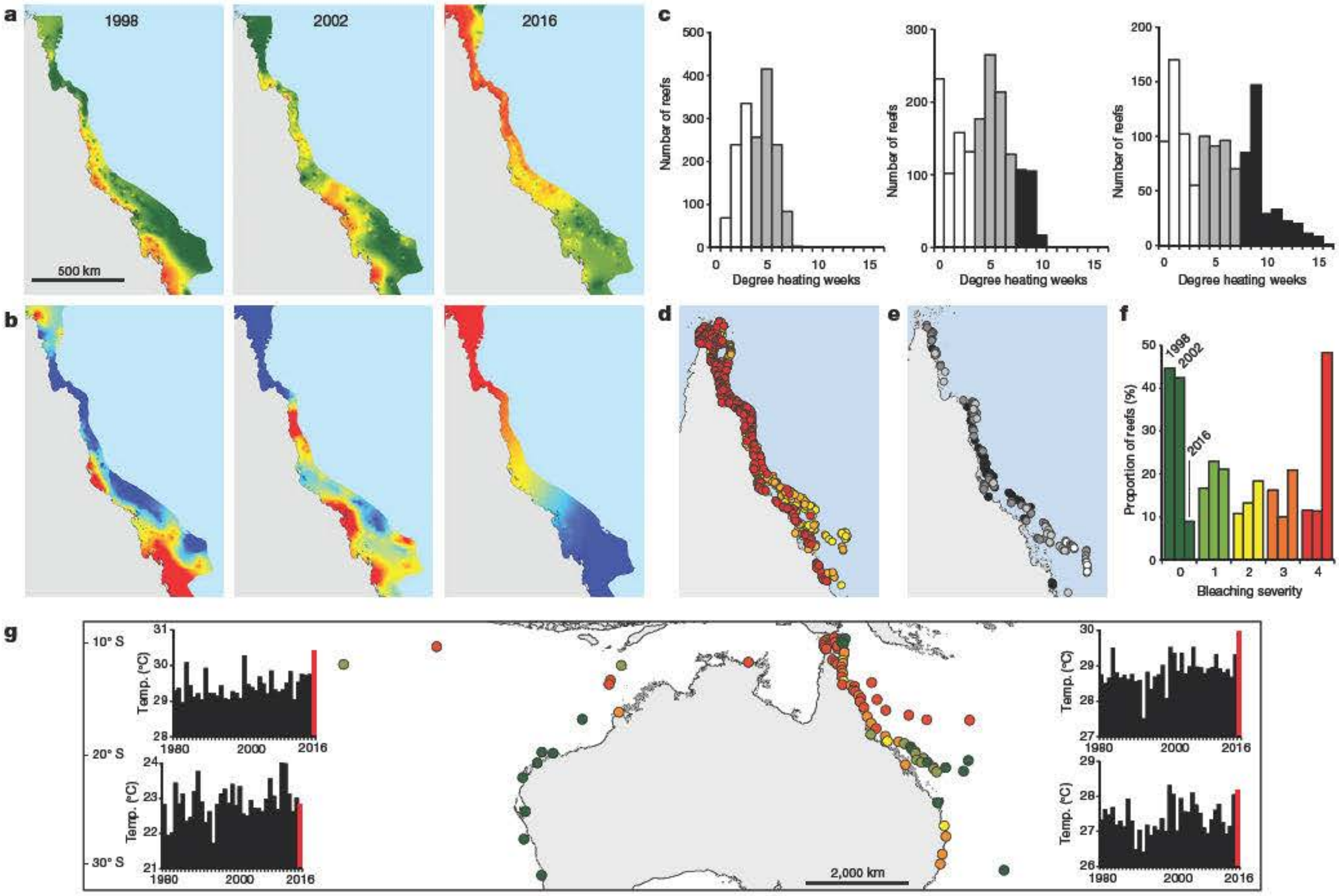

Figure 1 | Geographic extent and severity of recurrent coral bleaching at a regional scale, Australia. a, The footprint of bleaching on the Great Barrier Reef in 1998, 2002 and 2016, measured by extensive aerial surveys: dark green (<1% of corals bleached), light green (1–10%), yellow (10–30%), orange (30–60%), red (>60%). The number of reefs surveyed in each year was 638 (1998), 631 (2002), and 1,156 (2016). **b**, Spatial pattern of heat stress (DHWs; °C-weeks) during each mass-bleaching event. Dark blue indicates 0 DHW, and red is the maximum DHW for each year (7, 10 and 16, respectively). Orange and yellow indicate intermediate levels of heat exposure on a continuous scale. **c**, Frequency distribution of maximum DHWs on the Great Barrier Reef, in 1998, 2002 and 2016. White bars indicate 0–4 °C-weeks; grey bars, 4–8 °C-weeks; black bars, >8 °C-weeks. **d**, Locations of individual reefs that bleached (by >10% or more) in 1998, 2002 and/or 2016, showing the most severe bleaching score for reefs that were surveyed more than once. Yellow, 10–30% bleaching; orange, 30–60%; red, >60%. **e**, Location of reefs that were surveyed in all three years that bleached zero (white), one (light grey), two (dark grey) or three times (black). **f**, Frequency distribution of aerial bleaching scores for reefs surveyed in 1998 (left bars), 2002 (middle), and 2016 (right bars). Colour bleaching scores as in **a**. **g**, Bleaching severity during March to early April 2016 on both sides of Australia, including the Coral Sea and the eastern Indian Ocean. Colour bleaching scores as in **a**. Bar graphs show mean sea surface temperatures during March for each year from 1980 to 2016 for northern and southern latitudes on either side of Australia. The red bar highlights the north–south disparity in 2016. Map templates provided by Geoscience Australia under licence from Creative Commons Attribution 4.0 International Licence.

Reef. Consequently, the geographic pattern of severe bleaching in 2016 matched the strong north–south gradient in heat stress. By contrast, in 1998 and 2002, heat stress extremes and severe bleaching were both prominent further south (Fig. 1a, b). In 2016, severe bleaching (defined as an aerial score of >30% of corals bleached) was correctly predicted by satellite-derived DHWs in a statistical model, in 75% of cases (Extended Data Fig. 1 and Extended Data Table 1), similar to the amount of spatial variation in bleaching explained by temperature stress in 1998 and 2002 (ref. 8).

The geographic pattern of bleaching also demonstrates how marine heatwaves can be ameliorated by local weather[9], even during a global bleaching event. Arguably, southern reefs of the Great Barrier Reef would also have bleached in 2016 if wind, cloud cover and rain from ex-tropical cyclone Winston had not rescued them[10]. Winston passed over Fiji on February 20th, when the southern Great Barrier Reef was only 1 °C cooler than the north. By March 6th, this disparity increased to 4 °C (Extended Data Fig. 2). Corals in the south that had begun to pale in February regained their colour in the south in March, whereas bleaching continued to progress in central and northern sectors (Fig. 2a). Similarly, in western Australia in 2016, tropical cyclone Stan cooled down mid-coast regions in early February[11], and the Leeuwin Current (which transports warm tropical water southwards) was also weakened due to El Niño conditions[12]. Consequently, both sides of tropical and sub-tropical Australia, including offshore atolls in the Coral Sea and Indian Ocean, exhibited continental-scale latitudinal gradients in bleaching (Fig. 1g).

The local (individual reef)-scale pattern of recurrent bleaching on the Great Barrier Reef also reveals the trend of increasing severity and the erosion of potential spatial refugia. Of the 171 individual reefs that were aerially surveyed three times, 43% bleached in 1998, 56% in 2002, and 85% in 2016. Knowing the bleaching history of these well-studied reefs allows us to investigate why they have bleached zero, one, two or three times. Only 9% of these repeatedly surveyed reefs have never bleached, in most cases because they are located near the southern, offshore end of the Great Barrier Reef (Fig. 1e), where they have experienced relatively low temperature anomalies during each event. A further 26% of repeatedly surveyed reefs have bleached only once—10 reefs in 1998, 8 in 2002, and 32 for the first time in 2016. The latter

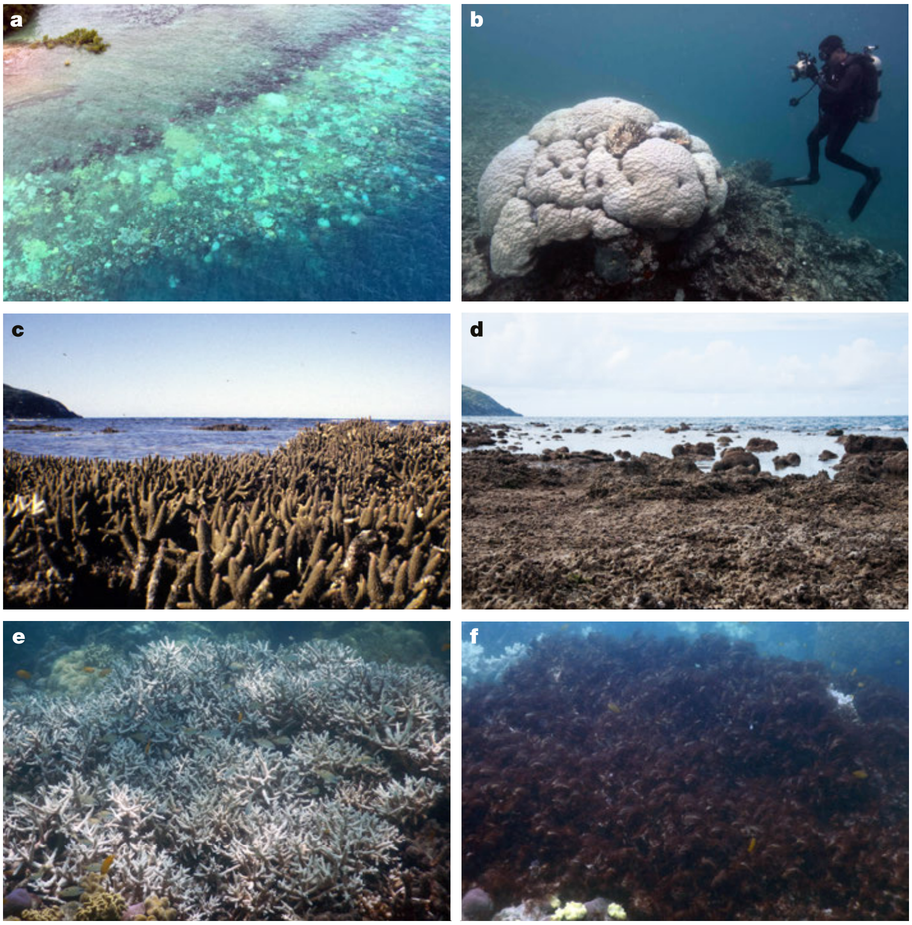

Figure 2 | Recurrent severe coral bleaching. a, Aerial view of severe bleaching in Princess Charlotte Bay, northeast Australia, March 2016. Close to 100% of corals are bleached on the reef flat and crest. Bleaching occurs when algal symbionts (*Symbiodinium* spp.) in a coral host are killed by environmental stress, revealing the white underlying skeleton of the coral. **b**, Severe bleaching in 2016 on the northern Great Barrier Reef affected even the largest and oldest corals, such as this slow-growing *Porites* colony. **c**, Large, old beds of clonal staghorn corals, *Acropora pulchra*, on Orpheus Island, Queensland photographed in 1997 were killed by the first major bleaching event on the Great Barrier Reef in 1998. **d**, Eighteen years later in May 2016, corals at this site have never recovered, with the original assemblages still visible as dead, unconsolidated and muddy rubble that is unsuitable for successful colonization by coral larvae. **e**, **f**, Mature stands of clonal staghorn corals were extirpated by heat stress and colonized by algae over a period of just a few weeks in 2016 on Lizard Island, Great Barrier Reef. Before (**e**) and after (**f**) photographs were taken on 26 February and 19 April 2016. Photo credits: **a**, J.T.K.; **b**, J. Marshall; **c**, B.W.; **d**, C.Y.K.; **e**, **f**, R. Streit.

were primarily in the northern sector of the Great Barrier Reef, which largely escaped bleaching in the two earlier events (Fig. 1a). Thirty-five per cent of the reefs have bleached twice, but only one reef bleached in both 1998 and 2002, compared to 58 reefs that bleached either in 1998 or 2002 and for a second time in the severe 2016 event. Finally, 29% of the repeatedly surveyed reefs bleached for a third time in 2016, primarily in central areas of the Great Barrier Reef, because they experienced anomalously warm temperatures during all three events (Fig. 1b, e). We conclude that the overlap of disparate geographic footprints of heat stress explains why different reefs have bleached 0–3 times, that is, the repeated exposure to unusually hot conditions is the primary driver of the likelihood of recurrent bleaching at the scale of both individual reefs and the entire Great Barrier Reef (Fig. 1a, b). We found a similar strong relationship between the amount of bleaching measured underwater, and the satellite-based estimates of heat exposure on individual reefs (Fig. 3). Low levels of bleaching were observed at some locations when DHW values were only 2–3 °C-weeks. Typically, 30–40% of corals bleached on reefs exposed to 4 °C-weeks, whereas an average of 70–90% of corals bleached on reefs that experienced 8 °C-weeks or more (Fig. 3).

Resistance and adaptation to bleaching

Once we account for the amount of heat stress experienced on each reef, adding chlorophyll *a*, a proxy for water quality, to our statistical model yielded no support for the hypothesis that good water quality confers resistance to bleaching[13]. Rather, the estimated effect of chlorophyll *a* was to significantly reduce the DHW threshold for bleaching (Extended Data Table 1). However, despite the statistical significance, the effect in real terms beyond heat stress alone is very small (Extended Data Fig. 1). Similarly, we found no effect of the level of protection (in fished or protected zones) on bleaching ($P > 0.1$: Extended Data Table 1). These results are consistent with the broad-scale pattern of severe bleaching in the northern Great Barrier Reef, which affected hundreds of reefs across inshore–offshore gradients in water quality and regardless of their zoning (protection) status (Fig. 1a, b).

Similarly, we find no evidence for a protective effect of past bleaching (for example, from acclimation or adaptation): reefs with higher bleaching scores in 1998 or 2002 did not experience less severe bleaching in 2016, after accounting for the relationship between the 2016 temperature stress and bleaching propensity ($P > 0.9$ in all cases; Extended Data Fig. 3). Thus, while several studies have indicated that prior exposure can influence the subsequent bleaching responses of corals[14–17], our comprehensive analysis of 171 repeatedly surveyed reefs indicates that any such historical effects on the Great Barrier Reef were masked by the severity of bleaching in 2016 (Fig. 2).

Winners and losers

Individual coral taxa bleached to different extents, especially on less-affected reefs, creating both winners (resistant corals) and losers

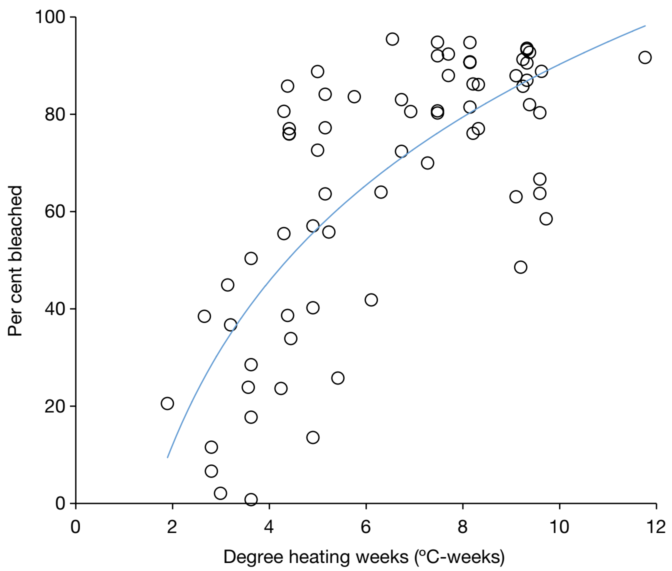

Figure 3 | The relationship between heat exposure (satellite-based DHWs in 2016) and the amount of bleaching measured underwater (per cent of corals bleached) in March/April. Each data point represents an individual reef ($n = 69$). The fitted line is $y = 48.6\ln(x) - 21.6$, $R^2 = 0.545$.

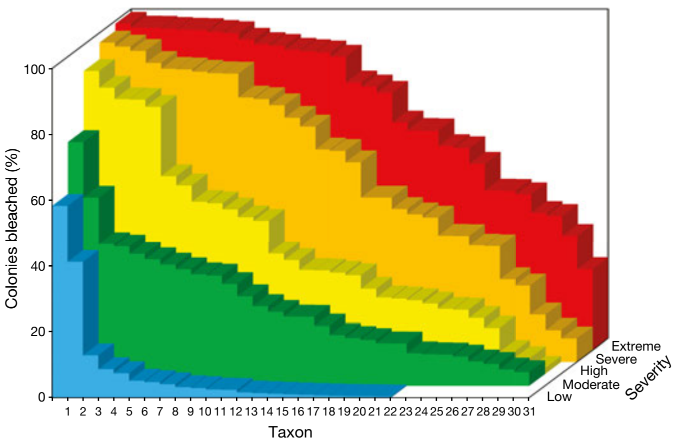

Figure 4 | Spectrum of bleaching responses by coral taxa on the Great Barrier Reef in 2016, with relative winners on the right, and losers on the left. Individual species or genera (58,414 colonies) are plotted in rank descending order along the x axis from high to low levels of bleaching, for different severities of reef bleaching. Reef-scale bleaching severities are: blue, 1–10% of all corals bleached; green, 10–30%; yellow, 30–60%; orange, 60–80%; and red, >80% bleached. See Extended Data Table 2 for taxonomic details.

(susceptible species), but the disparity among species diminished in the worst-affected, northern regions. (Fig. 4). At the population and assemblage level, when and where bleaching is severe, even century-old corals can bleach (Fig. 2b–d). By contrast, where bleaching is less intense, it is highly selective, with a broad spectrum of responses shown by winners versus losers; winners by definition bleach less and have higher survivorship[18–21]. On lightly and moderately bleached reefs (<10% or 10–30% of corals affected), predominantly in the southern Great Barrier Reef, many of the more robust coral taxa escaped with little or no bleaching in 2016. By contrast, on extremely bleached reefs in the north (60–80% or >80% overall bleaching), we found far fewer lightly bleached winners (Fig. 4). The rank order of winners versus losers also changed as the severity of bleaching increased (Extended Data Table 2), reflecting disparate responses by each taxon to the range of bleaching intensities. Thus, even species that are winners on relatively mildly bleached reefs joined the ranks of losers where bleaching was more intense (Fig. 4), creating a latitudinal gradient in the response of the coral assemblages.

The recovery time for coral species that are good colonizers and fast growers is 10–15 years[22–24], but when long-lived corals die from bleaching their replacement will necessarily take many decades. Recovery for long-lived species requires the sustained absence of another severe bleaching event (or other significant disturbance), which is no longer realistic while global temperatures continue to rise[25]. Therefore, the assemblage structure of corals is now likely to be permanently shifted at severely bleached locations in the northern Great Barrier Reef.

Implications for reef management

Our analysis has important implications for the management and conservation of coral reefs. We find that local management of coral reef fisheries and water quality affords little, if any, resistance to recurrent severe bleaching events: even the most highly protected reefs and near-pristine areas are highly susceptible to severe heat stress. On the remote northern Great Barrier Reef, hundreds of individual reefs were severely bleached in 2016 regardless of whether they were zoned as no-entry, no-fishing, or open to fishing, and irrespective of inshore–offshore differences in water quality (Fig. 1a and Extended Data Fig. 1). However, local protection of fish stocks and improved water quality may, given enough time, improve the prospects for recovery[3,4,26–29]. A key issue for all coral reefs is the frequency, or return time, of recurrent disturbance events, and whether there is sufficient time between successive bleachings for the re-assembly of mature coral assemblages. The chances of the northern Great Barrier Reef returning to its pre-bleaching assemblage structure are slim given the scale of damage that occurred in 2016 and the likelihood of a fourth bleaching event occurring within the next decade or two as global temperatures continue to rise.

Identifying and protecting spatial refugia is a common strategy for conservation of threatened species and ecosystems, including coral reefs[30]. However, our analyses indicate that the cumulative footprint of recurrent bleachings is expanding, and the number of potential refugia on the Great Barrier Reef is rapidly diminishing. Indeed, the remote northern region escaped serious damage in 1998 and 2002, but bore the brunt of extreme bleaching in 2016. Rather than relying on the premise of refugia, our results highlight the growing importance of promoting the recovery of reefs to recurrent bleaching events through local management of marine parks and water quality. However, bolstering resilience will become more challenging and less effective in coming decades because local interventions have had no discernible effect on resistance of corals to extreme heat stress, and, with the increasing frequency of severe bleaching events, the time for recovery is diminishing. Securing a future for coral reefs, including intensively managed ones such as the Great Barrier Reef, ultimately requires urgent and rapid action to reduce global warming.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Author Contributions The study was conceptualized by T.P.H. who wrote the first draft of the paper. All authors contributed to writing subsequent drafts. J.T.K. coordinated data compilation, analysis and graphics. Aerial bleaching surveys in 2016 of the Great Barrier Reef and Torres Strait were executed by J.T.K., T.P.H. and T.S., and in 1998 and 2002 by R.B. and D.R.W. Underwater bleaching censuses in 2016 were undertaken on the Great Barrier Reef by M.A.-N., A.H.B., D.R.B., M.B., N.E.C., C.Y.K., G.D.-P., A.S.H., M.O.H., E.V.K., M.J.M., R.J.P., M.S.P., G.T. and B.L.W., in the Coral Sea by T.C.B. and H.B.H., in subtropical Queensland and New South Wales by M.B., I.R.B., R.C.B., S.J.D., W.F.F., H.A.M., J.M.P. and B.S., off western Australia by R.C.B., S.C., J.P.G., J.-P.A.H., M.T.M., V.S. and S.K.W. J.G.A.-R., S.R.C., C.M.E., S.F.H., G.L., J.M.L. and W.J.S. undertook the analysis matching satellite data to the bleaching footprints on the Great Barrier Reef.

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METHODS

No statistical methods were used to predetermine sample size. The experiments were not randomized and the investigators were not blinded to allocation during experiments and outcome assessment.

Recurrent bleaching on the Great Barrier Reef. For 2016, comprehensive aerial surveys of the Great Barrier Reef Marine Park and Torres Strait reported in Fig. 1a were conducted on ten days between 22 March 2016 and 17 April 2016 when bleaching was particularly visible. We used light aircraft and a helicopter, flying at an elevation of approximately 150 m. A total of 1,156 individual reefs from the coast to the edge of the continental shelf were assessed along 14° of latitude (Extended Data Fig. 4). Each reef was assigned by visual assessment to one of five categories of bleaching severity, using the same protocols as earlier aerial surveys conducted in 1998 and 2002 by R.B.[8]: 0, <1% of corals bleached; 1, 1–10%; 2, 10–30%; 3, 30–60%; and 4, >60% of corals bleached. The accuracy of the scores was assessed by underwater ground-truthing (see next section). The aerial scores are presented in Fig. 1a as heat maps (stretch type: minimum–maximum) using inverse distance weighting (IDW; power, 2; cell size, 1,000; search radius, variable; 100 points) in ArcGIS 10.2.1.

Underwater surveys of eastern and western Australia. To ground-truth the accuracy of aerial scores of bleaching on the Great Barrier Reef (Fig. 1a), we conducted in-water surveys on 104 reefs during March and April 2016 (Extended Data Fig. 5). We also measured differential species responses (winners versus losers; Fig. 4) on 83 reefs, spanning the 1,200-km-long central and northern Great Barrier Reef, from 10–19° S. We surveyed two sites per reef, using five 10 × 1 m belt transects placed on the reef crest at a depth of 2 m at each site. Observers identified and counted each coral colony and recorded a categorical bleaching score for each individual: 1, no bleaching; 2, pale; 3, 1–50% bleached; 4, 51–99% bleached; 5, 100% bleached; 6, bleached and recently dead. The site-level amount of bleaching for each taxon in Fig. 4 is the sum of categories 2–5. The number of colonies assessed was 58,414. A similar standardized protocol was used to measure amounts of bleaching for the Coral Sea, on sub-tropical reefs south of the Great Barrier Reef, and across 18° of latitude along the west coast of Australia (Fig. 1g).

Temperature and thermal stress. The spatial pattern of thermal stress on the Great Barrier Reef during each of the three major bleaching events (1998, 2002 and 2016; Fig. 1b, c) was quantified using the well-established DHW metric[31]. The DHW values were calculated using the optimum interpolation sea surface temperature (OISST)[32], because it provides a consistent measure of thermal stress for all three major bleaching events on the Great Barrier Reef. The baseline climatology for the DHW metric was calculated for 1985–2012, following ref. 33. DHW values are presented in Fig. 1b as heat maps (stretch type: minimum–maximum) using inverse distance weighting (IDW; power, 2; cell size, 1,000; search radius, variable; 100 points) in ArcGIS 10.2.1. For Fig. 1g, March temperatures were compiled from HadISST1 (ref. 34) from 1980–2016 for four regions: northwest Australia, 10.5–20.5° S; mid-west Australia, 20.5–30.5° S; northern Great Barrier Reef, 10.5–16.5° S; and southern Great Barrier Reef, 21.5–24.5°S.

Water quality metrics. We considered remotely sensed chlorophyll *a* and Secchi depth proxies as water quality metrics, measured for the Great Barrier Reef[35] over different averaging windows. Specifically, we used four averaging windows with respect to 2016 (1, 2 or 4 years before bleaching, and a long-term 1997–2016 average), and two different time periods (summer months only (December to May inclusive) and the entire year (June to May inclusive)). We also considered derived quantities from these estimates: the proportion of time that reefs exceeded an estimated water quality chlorophyll *a* threshold of 0.45 $\mu g\, l^{-1}$ (ref. 13) and Secchi depth exposure, again for four different averaging windows, and for the full year and for summer only. All of these metrics were significantly correlated with one another. In particular, long-term (1997–2016) average chlorophyll *a* concentration was very highly correlated with all other metrics (absolute value of Spearman's rank correlation coefficient averaged $r = 0.81$, and was never lower than 0.7). Therefore, to minimize the risk of type I errors, we used it as the water quality proxy in our analyses of bleaching, log-transformed to obtain a symmetric distribution of values.

Analysis of spatial patterns, resistance and adaptation. To model the factors affecting bleaching in 2016, we used aerial bleaching scores as a response variable; whether a reef was severely bleached (57% of reefs had a bleaching score of 3–4) or not (the remaining 43% of reefs had a bleaching score of 0–2), for all surveyed reefs in the Great Barrier Reef Marine Park. We considered temperature stress (measured as DHW, described above), water quality (measured as the natural logarithm of long-term chlorophyll *a* concentration), and marine protection status. Reefs in three zones classified as 'Marine National Park', 'Preservation', 'Scientific Research', and 'Buffer' were considered to be protected in the model, whereas all other zones were fished. We repeated our test using other splits of bleaching scores (0 versus 1–4, 0–1 versus 2–4, and 0–3 versus 4), although these led to more uneven splits of the data. Regardless of how the bleaching scores were binned, the severity of bleaching was significantly correlated with DHW, while the additional variables had effects that were similar to our original analysis: small in magnitude or statistically non-significant.

To calibrate the relationship between temperature and bleaching, we fit a generalized linear model (GLM) with binomial error structure, using DHW as the explanatory variable. To test the hypothesis that high water quality confers bleaching resistance[13], we fit a model including both DHW and chlorophyll *a* as explanatory variables, and tested whether the effect of chlorophyll *a* concentration was significantly positive (that is, if reefs with higher chlorophyll *a* concentrations had a higher probability of bleaching). Similarly, to test the hypothesis that fishing increases bleaching resistance, we fit a model including DHW and protection status as explanatory variables, and tested whether the effect of protection was significantly negative (protected reefs had a lower probability of bleaching, at a given level of temperature stress, than fished reefs, see Extended Data Fig. 1 and Extended Data Table 1).

To test for evidence of acclimation or adaptation, we extracted the residuals from our DHW-only generalized linear model (Extended Data Table 1), and we tested for a negative correlation between the residuals and the aerial bleaching scores recorded during prior events: 1998, 2002 or the higher of the two earlier scores (Extended Data Fig. 1). That is, we tested the hypothesis that reefs that bleached more severely in prior events were less likely to bleach at a given temperature stress in 2016, compared to reefs that bleached less in prior events. Because bleaching score is ordered and categorical, we tested this hypothesis with Kendall's τ.

Data and code availability. Data and code available on request from the authors.

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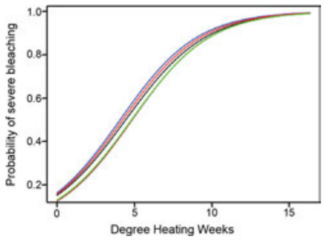
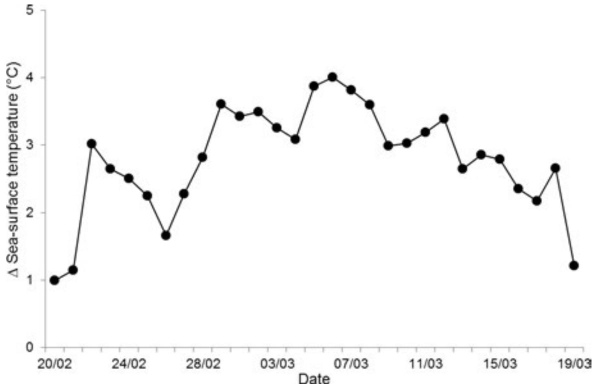
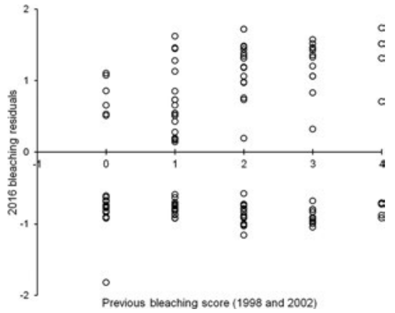


Extended Data Figure 1 | A generalized linear model to explain the severity of coral bleaching. Curves show the estimated relationships between probability of severe bleaching (>30%) on individual reefs of the Great Barrier Reef in 2016 and three explanatory variables (DHWs, chlorophyll *a*, and reef zoning, see Extended Data Table 1). The DHW-only model is shown in black. For the DHW plus chlorophyll *a* model, the blue threshold shows the estimated relationship between probability of severe bleaching and DHW for the 25th percentile of chlorophyll *a*, and the brown threshold shows the same for the 75th percentile of chlorophyll *a*. For the DHW plus reef zoning model, the red threshold shows the relationship for fished reefs, and the green for unfished reefs. Water-quality metrics and level of reef protection make little, if any, difference.

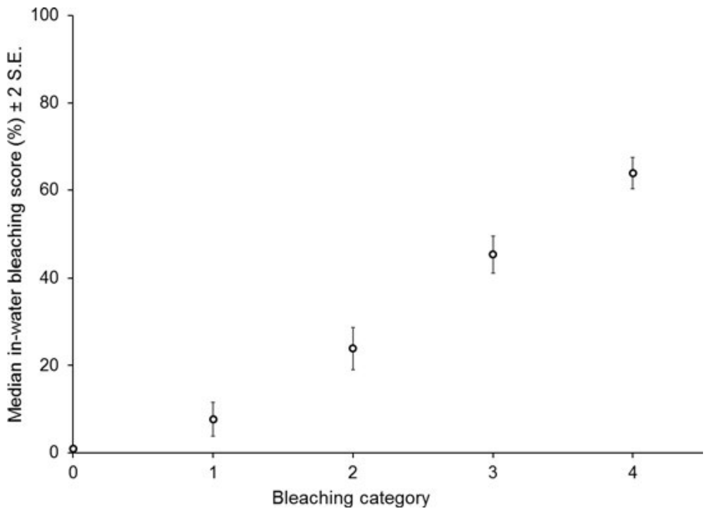


Extended Data Figure 2 | Difference in daily sea surface temperatures between the northern and southern Great Barrier Reef, before and after ex-tropical cyclone Winston. The disparity between Lizard Island (14.67° S) and Heron Island (23.44° S) increased from 1 °C in late February to 4 °C in early March 2016.



Extended Data Figure 3 | A test for the effect of past bleaching experience on the severity of bleaching in 2016. The relationship between previous bleaching scores (in 1998 or 2002, whichever was higher) and the residuals from the DHW generalized linear model (Extended Data Table 1). Each data point represents an individual reef that was scored repeatedly. There is no negative relationship to support acclimation or adaptation.

Extended Data Figure 4 | Flight tracks of aerial surveys of coral bleaching, conducted along and across the Great Barrier Reef and Torres Strait in March and April 2016. Blue colour represents land, white colour represents open water.



Extended Data Figure 5 | Ground-truthing comparisons of aerial and underwater bleaching scores. Aerial scores are: 0 (<1% of colonies bleached), 1 (1–10%), 2 (10–30%), 3 (30–60%) and 4 (60–100%) on the Great Barrier Reef in 2016 (Fig. 1a). Continuous (0–100%) underwater scores are based on *in situ* observations from 259 sites (104 reefs). Error bars indicate two standard errors both above and below the median underwater score, separately for each aerial category.

Extended Data Table 1 | A test for the causes of coral bleaching

A)

	Estimate	Std. Error	z value	Pr(>|z|)
Intercept	-1.725	0.145	-11.88	<0.001
DHW	0.388	0.029	13.63	<0.001

B)

	Estimate	Std. Error	z value	Pr(>|z|)
Intercept	-1.988	0.177	-11.211	<0.001
DHW	0.402	0.030	13.724	<0.001
Log(chlorophyll)	-0.520	0.185	-2.805	0.005

C)

	Estimate	Std. Error	z value	Pr(>|z|)
Intercept	-1.682	0.149	-11.312	<0.001
DHW	0.395	0.029	13.543	<0.001
Zoning(protected)	-0.223	0.175	-1.272	0.203

Generalized linear models (GLM) show the relationship between severe bleaching of reefs (>30%) in 2016 on the Great Barrier Reef and three explanatory variables. **a**–**c**, Explanatory variables were DHWs (**a**), DHW plus water quality (natural logarithm of chlorophyll-*a* concentration) (**b**), and DHW plus reef zoning (protected or fished) (**c**). Note that the estimated effect of chlorophyll *a* is negative, contrary to the hypothesis that good water quality confers resistance to bleaching.

Extended Data Table 2 | Winners and losers

Taxa	<10% bleaching	10-30% bleaching	30-60% bleaching	60-80% bleaching	>80% bleaching
Goniastrea retiformis	1	1	3	2	2
Goniastrea others	2	7	9	6	9
Pocillopora others	3	25	17	25	23
Symphyllia	4	30	30	30	30
Leptoria	5	4	5	4	13
Acropora - digitate	6	15	11	5	3
Acanthastrea	7	17	20	18	27
Galaxea	8	19	19	24	20
Fungiidae	9	26	21	23	28
Porites - massive	10	24	26	22	18
Goniopora	11	27	29	31	31
Stylophora	12	2	4	7	6
Seriatopora	13	3	2	1	8
Isopora	14	9	8	3	5
Pocillopora damicornis	15	6	7	16	11
Acropora - corymbose	16	21	13	11	7
Platygyra	17	5	16	12	10
Montipora	18	14	15	15	19
Acropora - tabular	19	23	14	9	4
Dipsastraea	20	8	18	17	17
Acropora - arborescent	21	12	6	8	1
Favites	22	13	12	10	12
Agaricidae	23	18	22	29	22
Echinopora	24	20	27	26	29
Hydnophora	25	10	23	19	24
Lobophyllia	26	28	31	28	25
Merulina	27	11	10	14	16
Milleporidae	28	16	1	21	14
Porites - branching	29	29	25	20	21
soft coral	30	22	24	13	15
Turbinaria	31	31	28	27	26

Rank order of taxa, from most bleached to least bleached, for different severities of bleaching. See Fig. 4.