CLIMATE COUNCIL

UPDATE 2018

LETHAL CONSEQUENCES: CLIMATE CHANGE IMPACTS ON THE GREAT BARRIER REEF

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Published by the Climate Council of Australia Limited

ISBN: 978-1-925573-62-6 (print)
978-1-925573-63-3 (digital)

Lethal Consequences: Climate Change Impacts on the Great Barrier Reef.
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Cover photo: 'Graveyard of Staghorn coral, Yonge reef, Northern Great Barrier Reef, October 2016' by Greg Torda ARC Centre of Excellence for Coral Reef Studies (CC BY-ND 2.0).

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Preface

In 2016 and 2017 the Great Barrier Reef experienced unprecedented back-to-back mass bleaching events, driven by marine heatwaves. The 2016 bleaching event was focused on the northernmost section of the reef between Lizard Island and the Torres Strait, and the 2017 bleaching event was focused on the central section of the reef but also extended into the northernmost section. This report provides an update on the impacts and threats of climate change on the Great Barrier Reef, following previous reports published by the Climate Council: 'Climate change: A deadly threat to coral reefs' (April 2017) and 'Australia's coral reefs under threat from climate change' (May 2016). This update highlights the coral mortality that has occurred from the combination of the 2016 and 2017 events.

Almost a third of the coral across the entire Great Barrier Reef died either during or in the eight-month period following the 2016 bleaching event, due to thermal stress. The distribution of mortality is closely correlated with the spatial extent of heat exposure during the event. Heat susceptible fast-growing corals such as staghorns and tabular species were the most severely affected, suffering devastating die-offs during and in the aftermath of bleaching. Average coral cover in the northern section of the reef is now at its lowest point on record, and coral cover in the central section of the reef declined from 22 percent in 2016 to 14 percent in 2018, largely due to the 2017 bleaching event. The resulting change in the composition of coral reefs may be irreversible. Further, the coral mortality has led to a decline in the diversity of fish species, and in the number of juvenile fish settling on the reef.

Rising average sea surface temperatures have increased the odds of marine heatwaves occurring, increasing their frequency and duration. The average return period of global mass bleaching events has decreased by 4.6-fold since the 1980s and is now around six years. This is not sustainable because repeated bleaching events will continuously set back recovery. At the same time, other threats of climate change to the reef include ocean acidification and the increasing intensity of tropical cyclones, which will increasingly undermine reef resilience.

Although local stressors such as sediment run-off and crown-of-thorns starfish are exacerbating the poor health status of the reef, local management solutions will not be enough, on their own, to reduce the vulnerability of reefs to the overarching threats from climate change. Unless deep cuts in greenhouse gas emissions are made as a matter of urgency - commensurate with limiting global average temperature rise to no more than 1.5°C above pre-industrial levels – the reef stands little chance no matter what measures are taken to enhance its resilience. A 2°C rise in average global temperature will almost certainly mean the collapse of warm water tropical reefs around the world. The decisions and actions that we take today to reduce greenhouse pollution will have a critical effect on the long-term survival of the iconic Great Barrier Reef.

Key Findings

1

Unprecedented bleaching events on the Great Barrier Reef in 2016 and 2017 have resulted in mass coral mortality.

- Nearly 30 percent of corals on the reef died as a result of the 2016 event, the worst the reef has ever experienced. Seventy-five percent of this mortality occurred in the northern section of the reef, where 93 percent of individual reefs between Port Douglas and the Torres Strait were affected.

- Mean coral cover in the central section of the reef has declined from 22 percent to 14 percent as a result of the bleaching.

- Fast-growing corals such as staghorns and tabular species were particularly susceptible to bleaching and have suffered a "catastrophic die-off". Many of the surviving corals are now weak, fragmented and susceptible to outbreaks of disease.

- Coral mortality has reduced the availability of habitat for fish, leading to a decline in reef fish diversity. Juvenile fish at Lizard Island, for example, have suffered a 40 percent decrease in settlement.

2

The 2016 bleaching event was at least 175 times more likely to occur due to climate change.

- Corals are at risk of bleaching when sea surface temperatures reach 1 to 1.5°C above the seasonal maximum mean temperature.

- In 2016, the Great Barrier Reef recorded its hottest sea surface temperatures for February, March and April since records began in 1900.

- Coral mortality both during, and in the eight-month period after the 2016 bleaching event was closely correlated with marine heat exposure, driven by climate change.

3

Rising sea surface temperatures over the past century have resulted in more frequent and prolonged global marine heatwaves.

- Global sea surface temperatures have increased by over 0.2°C from 1992 to 2010, increasing the odds of more frequent and prolonged marine heatwaves.
- From the 1925–1954 period to the 1987–2016 period, the global average frequency of marine heatwaves increased by 34 percent and the global average duration increased by 17 percent.
- The return period for global bleaching events has decreased from 27 years in the 1980s to only 5.9 years now.

4

The future of coral reefs around the world depends on how much and how fast we reduce greenhouse gas pollution levels now and in the coming years and decades.

- The likelihood that the Great Barrier Reef will ever fully recover or return to its pre-bleaching state is low.
- There is little evidence that improving water quality can sufficiently reduce susceptibility of corals to bleaching from marine heatwaves.
- By 2034, the extreme ocean temperatures that led to the 2016 and 2017 bleaching events may occur every two years under current greenhouse gas pollution rates, effectively destroying the Great Barrier Reef.
- Limiting temperature rise above pre-industrial levels to no more than 1.5°C is critical for the survival of reefs worldwide.

Contents

1. Unprecedented bleaching events on the reef

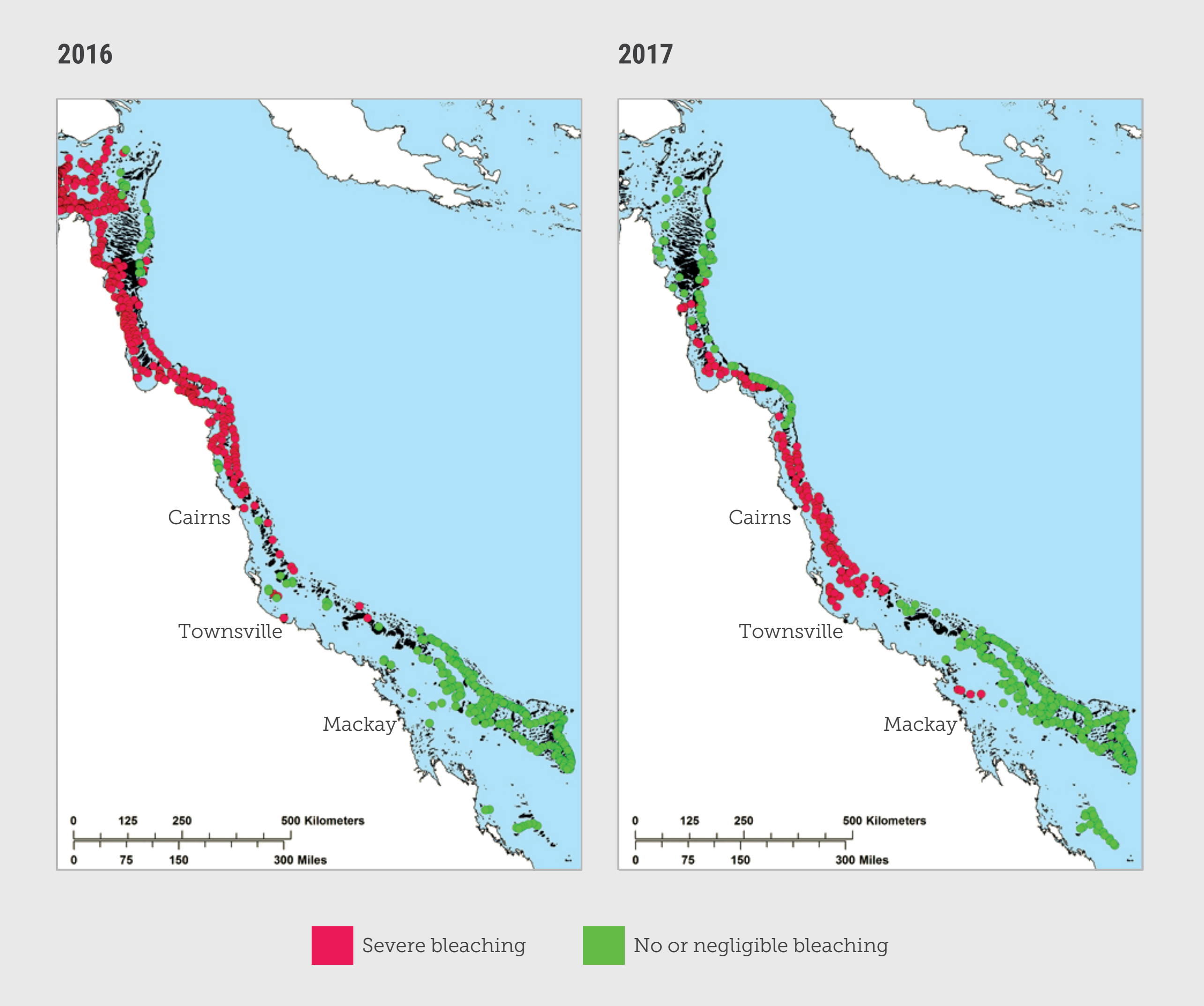
The Great Barrier Reef is the single largest living marine structure on Earth and one of the world's seven natural wonders. The Reef is a storehouse of extraordinary biodiversity and provides numerous ecosystem services. It is also a multi-billion dollar economic asset, with a value-added contribution to the Australian economy of around $6.4 billion per year, supporting 64,000 jobs (Deloitte Access Economics 2017). The overall economic, social and iconic value of the Great Barrier Reef has been conservatively estimated at around $56 billion (Deloitte Access Economics 2017).

In 2016 high sea surface temperatures driven by human-caused climate change and an El Niño event triggered the worst recorded bleaching on the Great Barrier Reef. The most severe bleaching occurred in the northernmost section of the reef between Port Douglas and the Torres Strait. Aerial and underwater surveys revealed that 93 percent of individual reefs were affected (Coral COE 2016).

In March 2017, less than 12 months after the 2016 bleaching event, another major bleaching event occurred, once more driven by severe marine heatwaves. This bleaching event was the first major event to occur without an El Niño event (when the risks of bleaching are higher). Bleaching occurred in the northern and central sections of the reef, extending 500 km south of the previous bleaching. Aerial surveys showed that the worst bleaching occurred in the central section between Cairns and Townsville (see Figure 1) (GBRMPA and AIMS 2017).

The Great Barrier Reef is a storehouse of biodiversity, and a multi-billion dollar tourist attraction, with an economic, social and iconic value of around $56 billion.

Figure 1: Spatial extent of bleaching on the Great Barrier Reef in 2016 and 2017 (adapted from GBRMPA 2017a).



The 2016 bleaching event was at least 175 times more likely to occur due to climate change.

Corals are at risk of bleaching when sea surface temperatures reach 1 to 1.5°C above the seasonal maximum mean temperature (Baker et al. 2008). In 2016, the Great Barrier Reef recorded its hottest sea surface temperatures for February, March and April since records began in 1900. Sea surface temperatures were 29.1°C in February (1.1°C above the 1961-1990 average), 29.1°C in March (1.3°C above average) and 27.8 °C in April (1.0°C above average) (BoM 2016). The conditions that precipitated the 2016 bleaching event were made 175 times more likely by climate change (King et al. 2016).

March 2017 was the second hottest March on record (following 2016) (BoM 2017). As a whole, 2017 was also the hottest non-El Niño year on record relative to the average temperature between 1981-2010 (WMO 2018). The 2016 bleaching event was the worst that the reef has ever experienced and the 2017 bleaching followed closely behind.

2. What causes coral bleaching?

Corals have an interdependent relationship with tiny single celled plant-like organisms called *zooxanthellae* that live within their tissues, giving the corals their characteristic colour (NOAA 2015a, 2015b). Corals provide habitat for the *zooxanthellae*, while the algae provide the corals with food, producing as much as 90 percent of the energy the corals need to grow and reproduce (AIMS 2016; GBRMPA 2016).

When corals become stressed, they lose the *zooxanthellae*, revealing the white skeleton of the coral, hence the term "bleaching" (see Figure 2). Bleaching can occur when corals are subject to sea surface temperatures only 1 to 2°C above long-term average maximum temperatures (De'ath et al. 2012; Hoegh-Guldberg et al. 2014). If the thermal stress is mild or short-lived, the corals may survive. If the stress is more severe or prolonged, the corals can die or partially die (Putnam and Edwards 2011; Sammarco and Strychar 2013; NOAA 2015b). Repeated, lower level bleaching events can also lead to loss of corals over time (De'ath et al. 2012). Corals that survive bleaching may have slower growth, decreased reproduction and be more susceptible to disease (see Figure 3) (GBRMPA 2016).

Figure 2: Bleached staghorn coral.

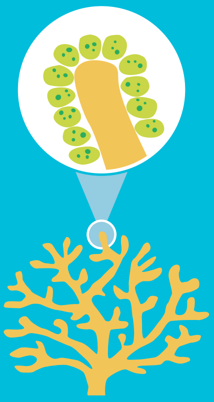
WHAT IS CORAL BLEACHING?

Coral reefs are highly vulnerable to a changing climate. Warmer ocean temperatures and other stressors cause coral bleaching events which can damage and destroy coral reefs and the ecosystems they support.

1 HEALTHY CORAL

Coral and algae depend on each other to survive.

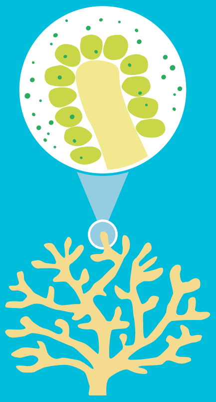
Corals have a symbiotic relationship with microscopic algae called zooxanthellae that live in their tissues. These algae provide their host coral with food and give them their colour.



2 STRESSED CORAL

If stressed, algae leave the coral.

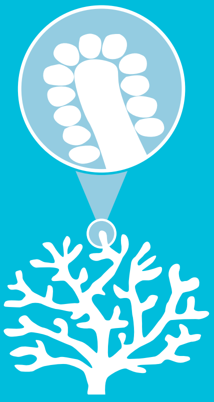
When the symbiotic relationship becomes stressed due to increased ocean temperature or pollution, the algae leave the coral's tissue.



3 BLEACHED CORAL

Coral is left bleached and vulnerable.

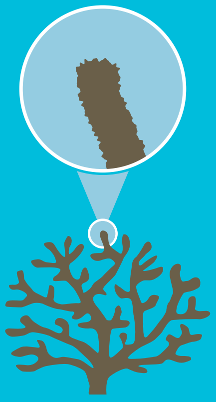
Without the algae, the coral loses its major source of food, turns white or very pale, and is more susceptible to disease.



4 DEAD CORAL

Coral is left bleached and vulnerable.

Without enough plant cells to provide the coral with the food it needs, the coral soon starves or becomes diseased. Soon afterwards, the tissues of the coral disappear and the exposed skeleton gets covered with algae.



CHANGE IN OCEAN TEMPERATURE

Increased ocean temperature caused by climate change is the leading cause of coral bleaching. Water temperature higher than the average summer maximum – just 1°C higher for four weeks – can cause bleaching.

RUNOFF AND POLLUTION

Storm generated precipitation can rapidly dilute ocean water and runoff can carry pollutants - these can bleach near shore corals.

OVEREXPOSURE TO SUNLIGHT

When temperatures are high, high solar irradiance contributes to bleaching in shallow-water corals.

EXTREME LOW TIDES

Exposure to air during extreme low tides can cause bleaching in shallow corals.

Figure 3: Causes and impacts of coral bleaching. Adapted from NOAA 2015b; Underwater Earth 2015.

3. Coral mortality following bleaching events

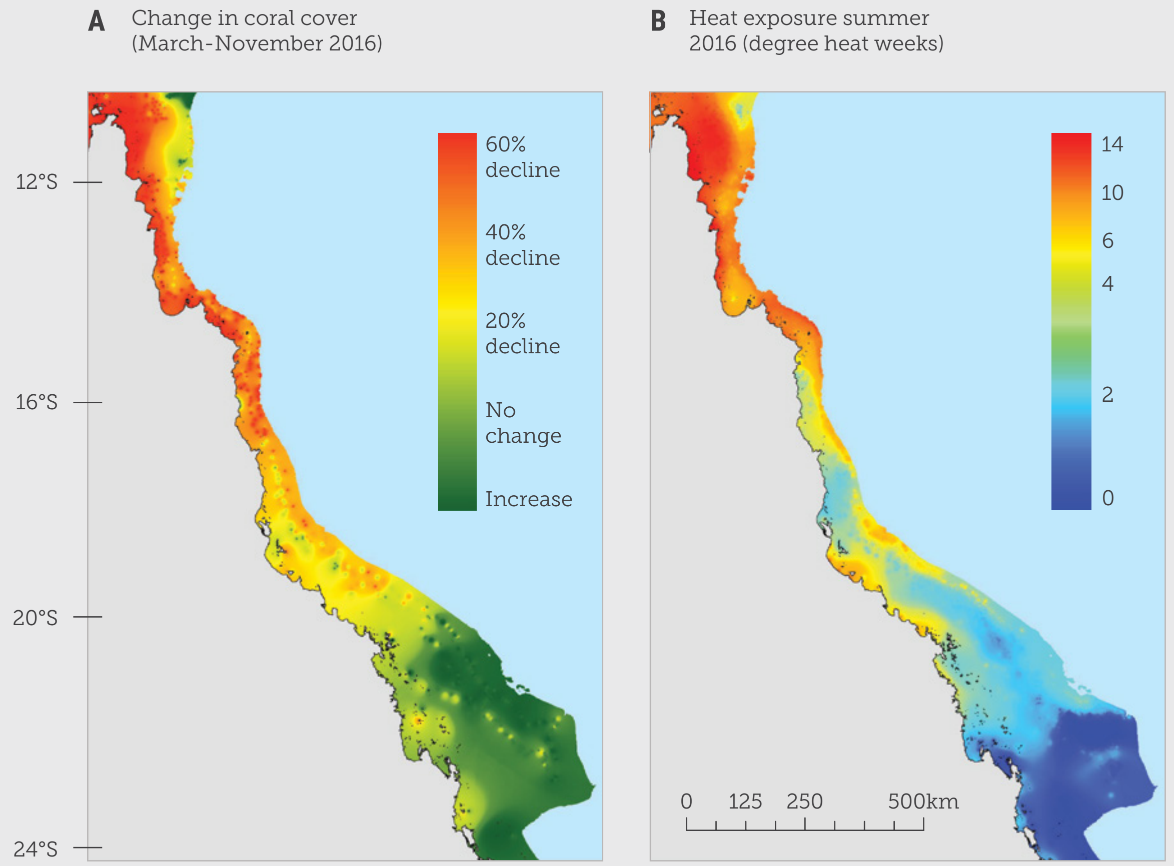
Significant coral mortality on the Great Barrier Reef occurred as a result of the 2016 bleaching event. During the event, corals started to die almost immediately when heat exposure reached a threshold of 3-4°C-weeks (degree heating weeks – a commonly used measure of heat exposure based on the intensity and duration of thermal stress). Coral mortality during the bleaching event was strongly correlated with the level of heat exposure. For example, heat exposure of 4°C-weeks led to median coral loss of 5 percent or less, 4-8°C-weeks led to median coral loss of 15.6 percent and 8°C-weeks led to median coral loss of 20.7 percent (Hughes et al. 2018a).

Coral mortality continued to occur in the aftermath of the bleaching event. Mortality measured in the eight-month period following the bleaching was strongly correlated with both the level of bleaching and heat exposure. Where bleaching on reefs was less than 25 percent, post-bleaching mortality was negligible, but above this threshold, loss of corals progressively increased.

Reefs exposed to 0-3°C-weeks experienced low loss of coral. Above this threshold reefs experienced a progressive decline in coral following the bleaching event. Reefs exposed to 4°C-weeks experienced 40 percent loss of coral, reefs exposed to 8°C-weeks experienced 66 percent loss and reefs exposed to 9°C-weeks experienced >80 percent loss. Across the entire Great Barrier Reef, coral declined by 29 percent following the bleaching event (Hughes et al. 2018a).

The 2016 bleaching event resulted in the death of 29 percent of the corals on the Great Barrier Reef. Coral mortality during and after bleaching was strongly correlated with thermal exposure.

Figure 4: Spatial pattern of large-scale changes in coral cover in the eight-month period following the bleaching event of 2016. Change in coral cover is shown in (a) and heat exposure in (b) (adapted from Hughes et al. 2018a).



Around 75 percent of this mortality occurred in the northern section of the reef (GBRMPA 2017b). The spatial pattern of heat exposure and changes in coral cover measured in the eight-month period after the bleaching event are strongly correlated (Figure 4), consistent with the climate-change driven heatwave being the primary driver.

Mortality varied greatly for different types of corals, with fast growing species such as staghorns and tabular corals faring the worst. Reefs that experienced >60 percent bleaching suffered a "catastrophic die-off" of these fast-growing species, declining by more than 75 percent. Consequently, a dramatic shift in the composition of the reef has occurred over recent years and a marked simplification in its three-dimensional structure (see Figure 5) (Hughes et al. 2018a).

The overall decline in coral cover and the shift in coral assemblages has caused a sharp drop in the diversity of reef fish. Branching and tabular species provide ideal habitat for small fish to hide from larger predatory fish. Butterfly fish for example, which are highly dependent on branching staghorn species, notably declined following the bleaching event (Richardson et al. 2018).

Figure 5: Dead staghorn corals around Lizard Island, May 2016.

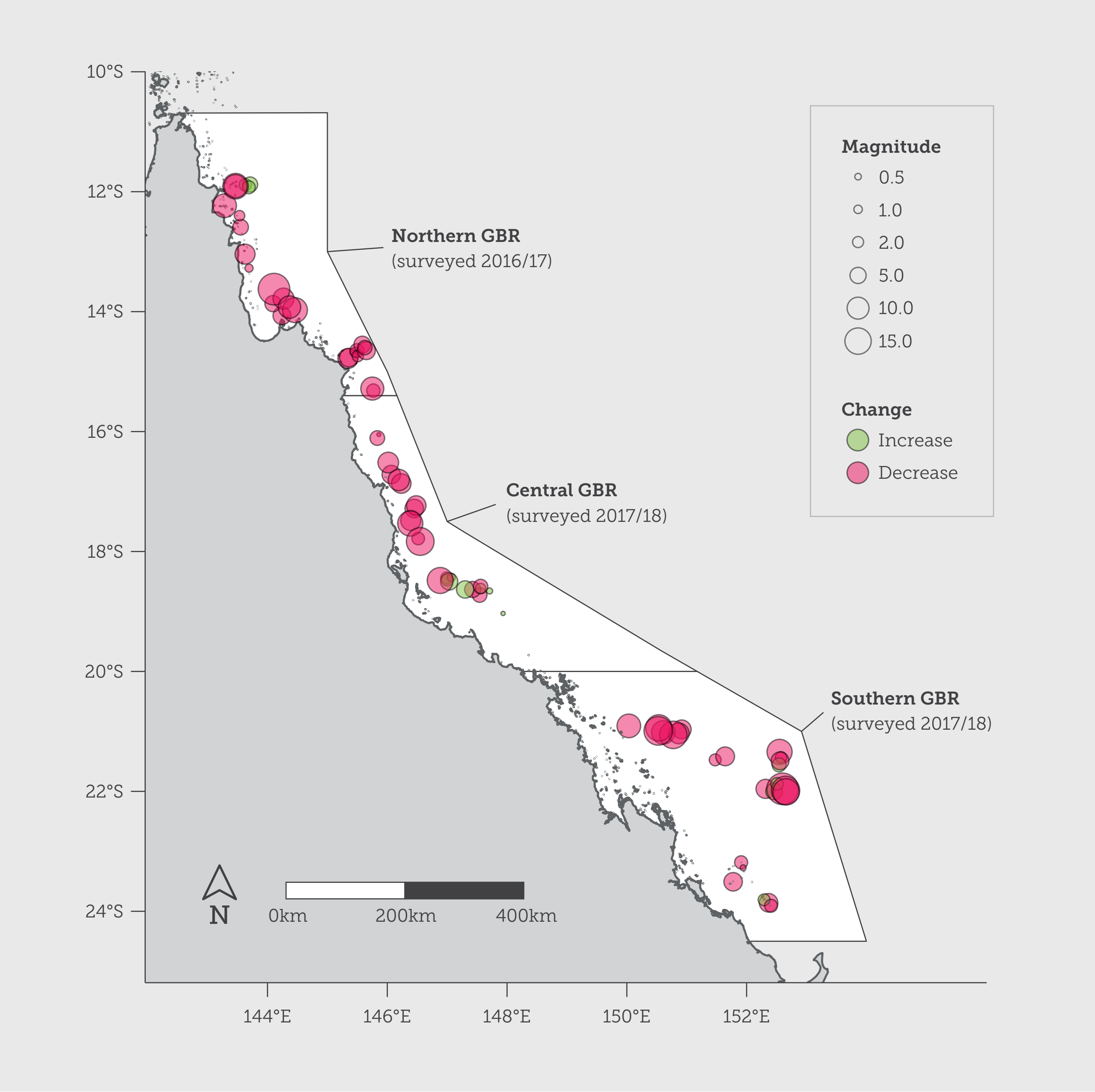
The degradation of the Great Barrier Reef has meant that many reefs are now much quieter than they were prior to the 2016 bleaching event. Invertebrates and fish on healthy coral reefs make many chirping, chattering, snapping and popping sounds. The soundscapes around Lizard Island are now less complex and on average 15 decibels (dB/1 μPa) quieter than before the 2016 bleaching event (Gordon et al. 2018). Reef soundscapes are now no more attractive to juvenile fish than the sound of the open ocean, resulting in 40 percent less settlement of juvenile fish compared to the period before the 2016 bleaching event (Gordon et al. 2018).

Surveys conducted by the Australian Institute of Marine Science's Long Term Monitoring Program show that average hard coral cover across all three sections of the Great Barrier Reef (southern, central and northern) is now in steep decline (AIMS 2018).

The northern section of the Great Barrier Reef, which experienced severe bleaching in 2016 and minor bleaching again in 2017, was not included in the latest round of surveys conducted by the Long Term Monitoring Program. However, the last surveys conducted in early 2017 (prior to the 2017 bleaching event) show that average coral cover in this section halved between 2013 and 2017, dropping to only 10 percent in early 2017 - the lowest on record. The steep decline in coral cover in the northern section can be attributed mainly to the severe bleaching in 2016 and two tropical cyclones that hit the northern section of the Great Barrier Reef between 2013 and 2017 (AIMS 2018).

More recent surveys carried out between September 2017 and May 2018 showed that mean coral cover in the central section of the reef has declined from around 22 percent in 2016 to 14 percent in 2018 due to the back-to-back bleaching events in 2016 and 2017 and increasing crown-of-thorns starfish activity (AIMS 2018).

Figure 6: Map shows reefs surveyed in 2016/2017 (northern section) and 2017/2018 (central and southern sections). The size and colour of circles depicts the direction and extent of change, showing that all sections have experienced recent steep declines in coral cover (adapted from AIMS 2017 and AIMS 2018).



In the southern section of the Great Barrier Reef that largely escaped bleaching during 2016 and 2017, average coral cover is much higher, but has still declined from around 33 percent in early 2017 to 25 percent in 2018, likely due to increasing crown-of-thorns starfish activity in this section. The recent simultaneous and steep declines in average hard coral cover in all three sections of the Great Barrier Reef is unprecedented in the 30-year history of the Long Term Monitoring Program (AIMS 2018).

The devastating impacts of bleaching on the Great Barrier Reef may be irreversible.

The likelihood that the composition of coral reefs will ever fully return to their pre-bleaching state is low (Hughes et al. 2018a). Some of the surviving corals are still dying as they remain weak, fragmented and susceptible to outbreaks of disease. Successful recruitment and development of new coral colonies will depend on sufficient supply of larvae from unbleached or lightly bleached corals, the breakdown of coral skeletons to provide a stable substrate for juvenile coral settlement, and the appropriate conditions for development. Even fast-growing corals take at least a decade to develop and if bleaching reoccurs during this period, it will set back or prevent recovery (Hughes et al. 2018a).

The 2016 and 2017 bleaching events have also affected the tourism industry around Cairns and Port Douglas, with a recent survey showing that the Great Barrier Reef slipped from being third on the list of reasons for domestic tourists to visit Cairns at the beginning of 2016, to 12th on the list by the third quarter of 2016. Prior to the 2017 bleaching event, the Great Barrier Reef had climbed back up to 7th position, but fell again to 9th following the 2017 bleaching event. The survey results showed that most domestic tourists were well aware of the coral bleaching events from media reporting. Around 90 percent of domestic tourists consistently expressed concern about coral bleaching over the 18 month period of the survey (Prideaux et al. 2018).

4. Projected impacts of climate change on reefs world-wide

Climate change, caused primarily by burning fossil fuels (coal, oil and gas), is driving a long-term trend of increasing average ocean and air temperatures in Australia and globally. More than 90 percent of the total energy accumulated between 1971 and 2010 has been absorbed by the oceans, and the upper 75 m - where most reef-building corals live - has warmed by 0.22°C over the period 1992 to 2010 (IPCC 2013).

This increase in average sea surface temperature is associated with an increase in the frequency and duration of marine heatwaves. Between the 1925–1954 and 1987–2016 periods, the global average frequency of marine heatwaves increased by 34 percent and the global average duration increased by 17 percent (Oliver et al. 2018). The increased duration and frequency of marine heatwaves has amounted to a 54 percent increase in marine heatwave days between the 1925-1954 and 1987-2016 periods. The increase in frequency and duration of marine heatwaves has largely occurred in the last few decades, indicating an accelerating trend (Oliver et al. 2018).

The increased frequency, intensity and duration of marine heatwaves has meant that, globally, the periods of time between bleaching events are getting shorter. Before human-driven warming of the climate, bleaching events were relatively rare and the return periods allowed for recovery of the reef between events. Recent research based on analysis of bleaching records from 1980 to 2016 at 100 reef locations across 54 countries has found that the average interval for bleaching events has shrunk 4.6-fold in the past three to four decades from 27 years to around 5.9 years (Hughes et al.

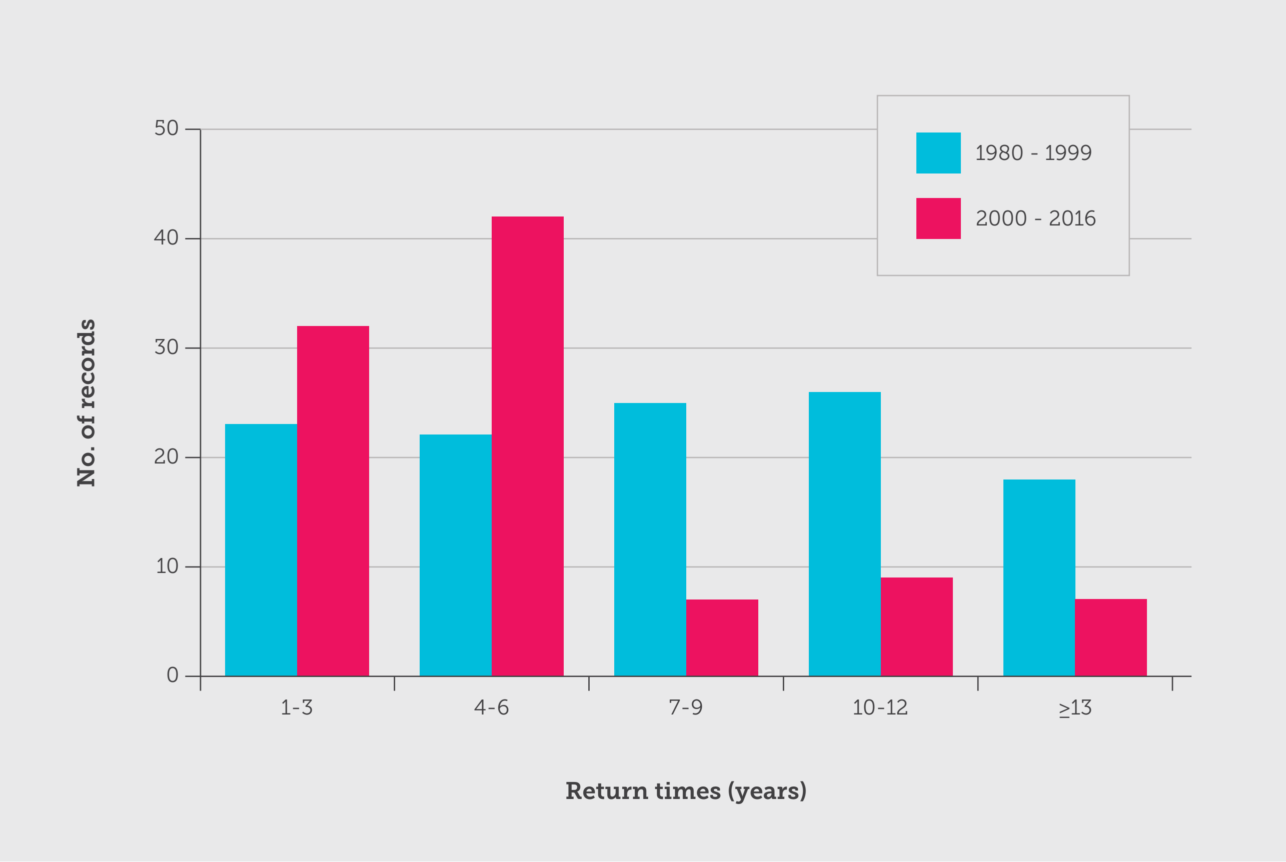
Rising global sea surface temperatures have increased the odds of marine heatwaves, which are now occurring 34 percent more frequently and lasting 17 percent longer than the average for the 1925-1954 period.

The average bleaching return period is now 5.9 years, whereas in the 1980s it was around 27 years.

2018b). One third of the return periods for bleaching events globally since 2000 have been between just one and three years (see Figure 7) (Hughes et al. 2018b).

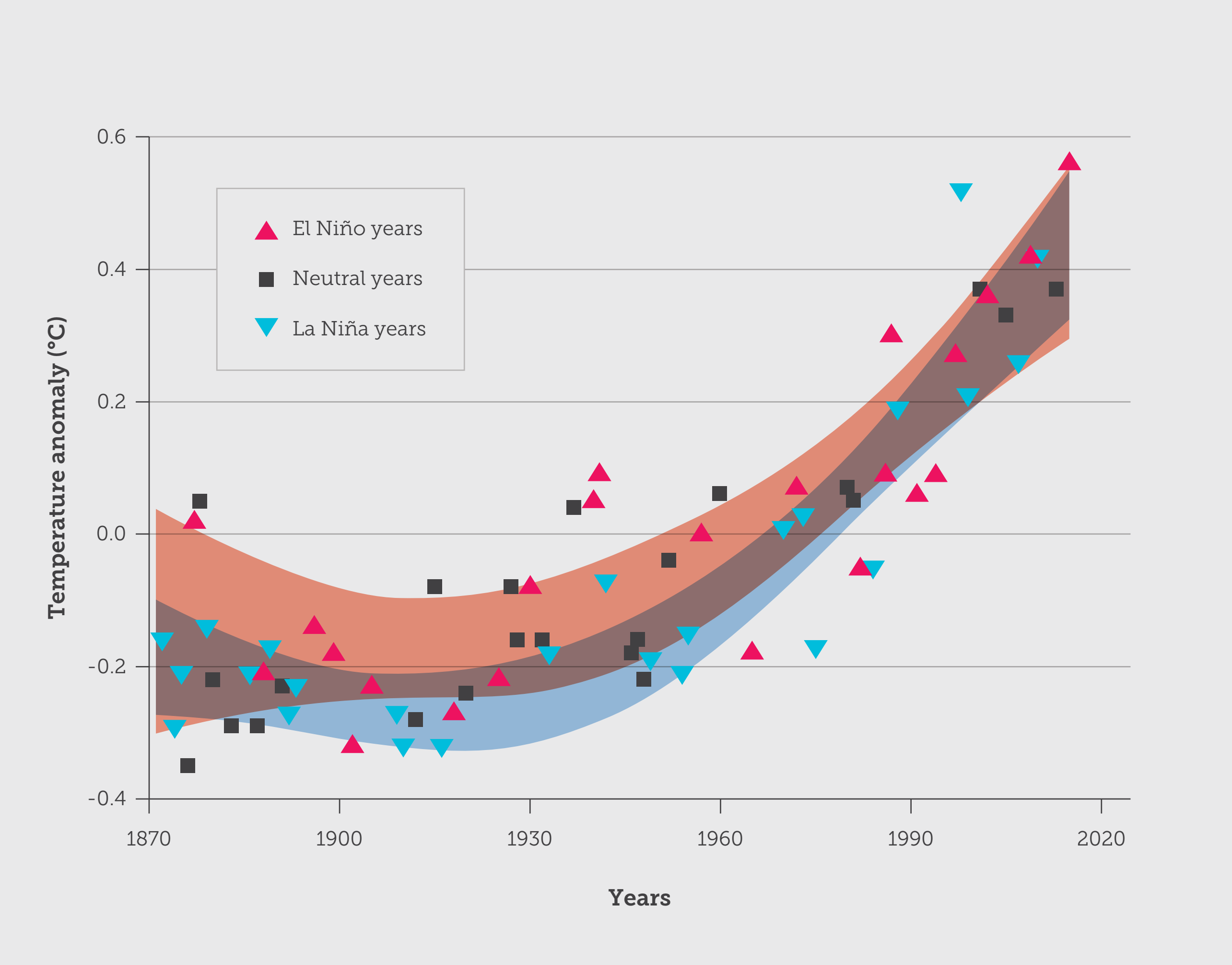
Bleaching events are also now occurring on a much larger scale than in the past. Before the 1980s, bleaching events were on a local scale (only tens of square kilometres), usually due to local stressors such as pollution or sedimentation. As sea surface temperatures have risen, the spatial extent of bleaching events has increased markedly (Hughes et al. 2018b).

Figure 7: Frequency distribution of return times (number of years) between severe bleaching events from 1980 to 1999 (blue bars) and 2000 to 2016 (magenta bars) (adapted from Hughes et al. 2018b).



In Australia, three out of four of the major bleaching events that have affected the Great Barrier Reef have occurred during El Niño years. The El Niño phase of ENSO refers to the extensive warming of the central and eastern Pacific Ocean that leads to a major shift in weather patterns across the Pacific. An El Niño event provides an extra boost to the global average temperature, typically around 0.1 – 0.2°C (Trenberth et al. 2002; Foster and Rahmstorf 2011). Conversely, during La Niña (the opposite phase of ENSO to El Niño) global average temperatures are somewhat cooler. The long-term trend in increasing temperatures means that temperatures during many La Niña periods are now warmer than during El Niño phases 30 to 40 years ago (see Figure 8) (Hughes et al. 2018b). As a result, coral bleaching is occurring more frequently in all ENSO phases and can be expected to occur in hot summers in both El Niño and La Niña years in the future (Hughes et al. 2018b).

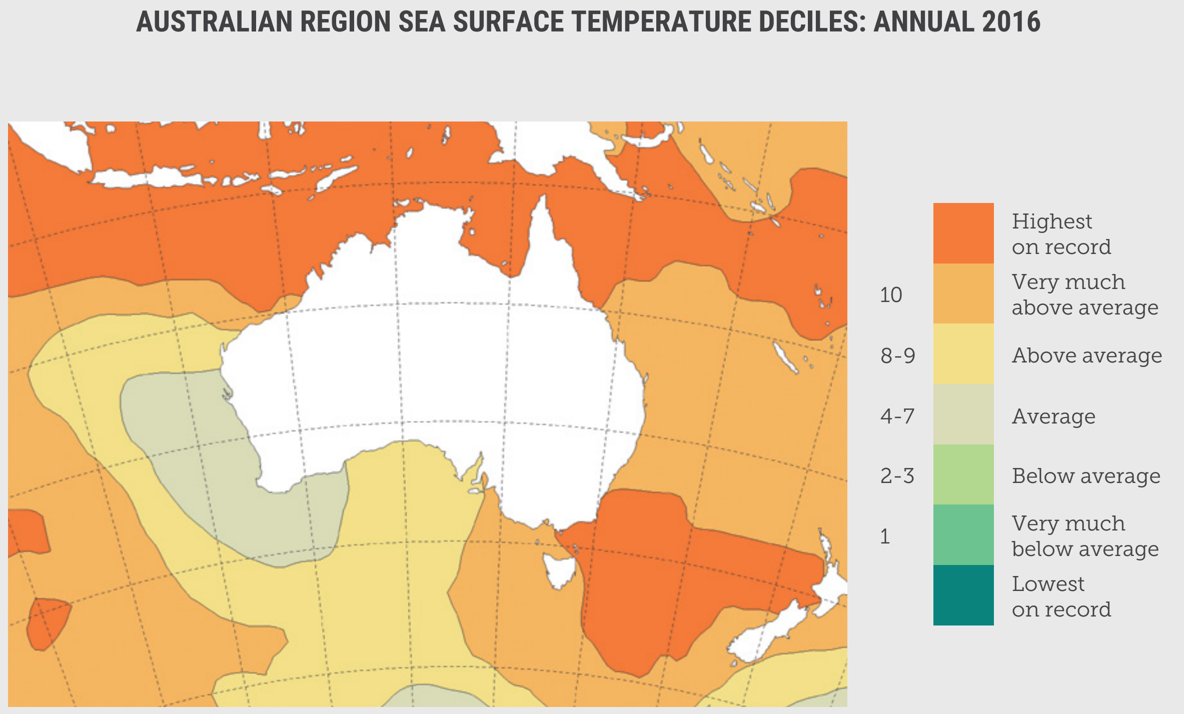
Figure 8: Sea surface temperature anomalies from 1871-2016 relative to 1961-1990. Upside down blue triangles show La Niña years, magenta triangles show El Niño years and black squares show neutral years. The magenta and blue bands show 95 percent confidence intervals for El Niño and La Niña years, respectively (adapted from Hughes et al. 2018b).



BOX 1: EL NIÑO IN AUSTRALIA

The El Niño phase of ENSO refers to the extensive warming of the central and eastern Pacific Ocean that leads to a major shift in weather patterns across the Pacific. In Australia, particularly eastern Australia, El Niño events are associated with an increased probability of drier conditions (BoM 2018). In addition to drier conditions in the east, El Niño events usually bring (i) warmer temperatures, including higher surface ocean temperatures along Australia's east coast; (ii) increased fire danger in the southeast; and (iii) reduced tropical cyclone frequency. Three out of four of the major bleaching events that have occurred on the Great Barrier Reef have occurred during an El Niño phase of the El Niño-Southern Oscillation (ENSO) phenomenon (1998, 2002 and 2016). Figure 9 below shows how the sea surface temperature in 2016 compared to the average annual sea surface temperature (based on records since 1900).

Figure 9: 2016 sea surface temperatures compared to historical records stretching back to 1900 (adapted from NOAA 2015c).



5. Other threats of climate change to the Great Barrier Reef

5.1 Tropical cyclones

Climate change also poses a number of other threats to coral reefs. A projected increase in the intensity of tropical cyclones will significantly increase the risk of physical damage from strong winds and waves. Tropical cyclones also bring heavy rainfall, which can cause flooding and sediment plumes causing coral stress.

Tropical cyclones have had devastating impacts on the Great Barrier Reef in recent years. One study showed that between 2009 and 2015, more than 68 percent of the total Great Barrier Reef shelf edge was affected by Category 5 cyclones (Cheal et al. 2017). Whilst damage from cyclones is generally more localised than damage from bleaching due to marine heatwaves, the consequences for fish and other marine organisms that depend on the reef can be worse, as coral structures are more readily decimated by the strong winds and waves generated by cyclones, reducing the three-dimensional structure of coral reefs that provides habitat.

Global studies project a shift in the distribution of tropical cyclones toward increased incidence of intense systems and decreased incidence of weaker systems (Bender et al. 2010; Done et al. 2015). One study simulated tropical cyclones since 1975 with and without human caused greenhouse gas pollution and found a shift in the distribution of tropical cyclones towards higher intensity with Category 4 and Category 5 cyclones increasing by ~25-30 percent per 1°C of global warming, balanced by a decrease in the prevalence of Category 1 and 2 cyclones (Holland and Bruyère 2014).

Climate change is projected to drive an increase in the frequency of high intensity tropical cyclones in northeastern Australia.

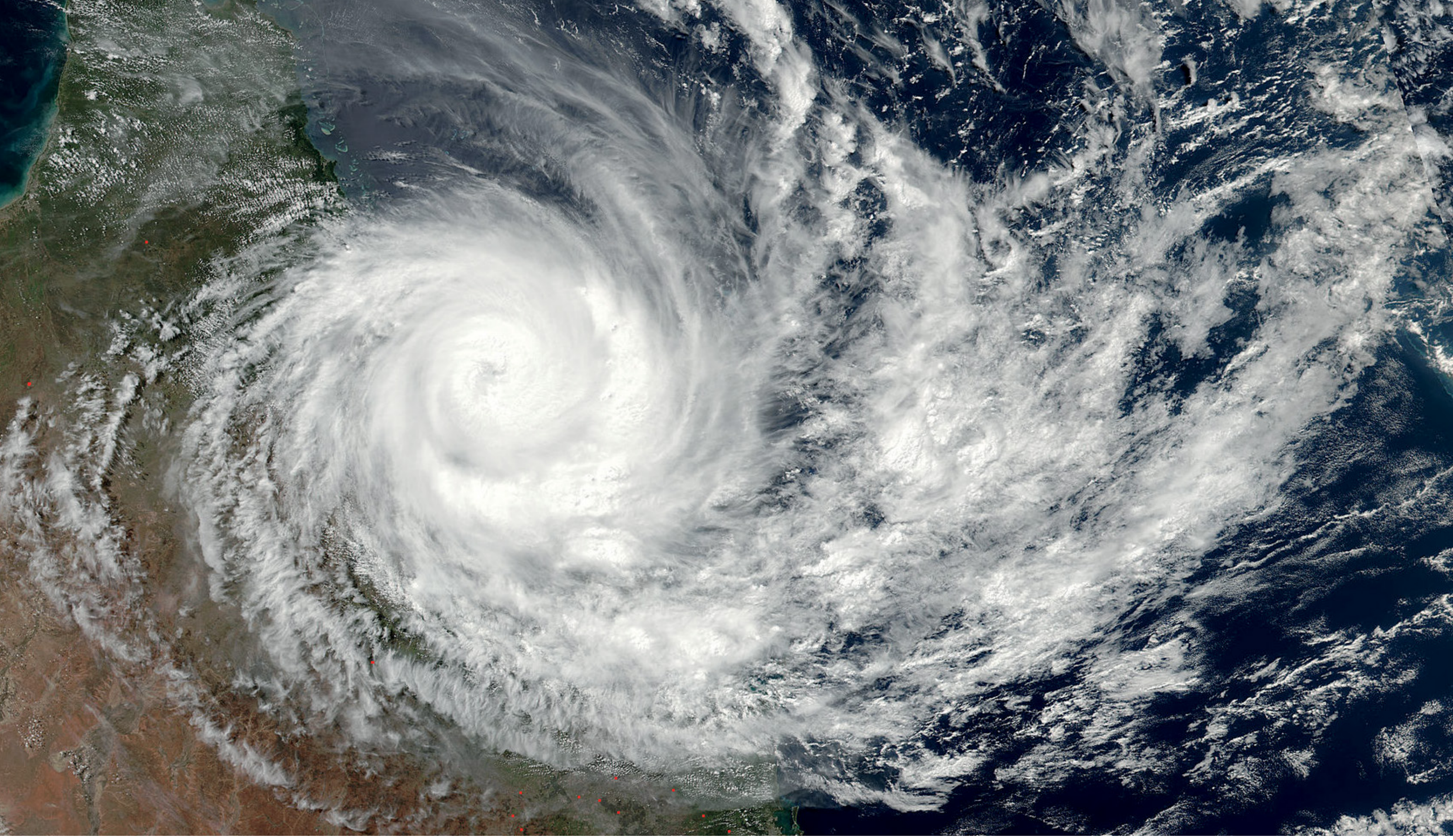


Figure 10: Tropical Cyclone Debbie makes landfall in Queensland, 29 March 2017.

Climate change is also projected to increase the proportion of higher intensity cyclones around Australia, with a possible decrease in overall frequency (CSIRO and BOM 2015). In the southern hemisphere and Australia, tropical cyclone detection prior to 1970 was weak, leading to low confidence in the relationships between climate change and tropical cyclones both historically and in the future (Walsh et al. 2012). Nevertheless, in the past two decades, northeastern Australia has experienced an increase in the frequency of intense tropical cyclones and heavy rainfall, and an increase in total rainfall (Beeden et al. 2015; Alexander 2007).

Since 2003, several high intensity tropical cyclones have affected the Great Barrier Reef, including:

- Ingrid (cat 4, 2005)
- Monica (cat 5, 2006)
- Larry (cat 4, 2006)
- Hamish (cat 4, 2009)
- Ului (cat 5, 2010)
- Yasi (cat 5, 2011)
- Ita (cat 5, 2014)
- Marcia (cat 4, 2015) and
- Debbie (cat 4, 2017)

By contrast, in the three decades between 1970 and 2003, no cyclones above Category 1 were recorded over the Great Barrier Reef (Puotinen 1997; Puotinen 2007).

5.2 Ocean acidification

Another factor that is exacerbating degradation of reef systems is the uptake of carbon dioxide by the oceans, causing acidification. Oceans absorb roughly one quarter of the carbon dioxide emissions released into the atmosphere each year (Albright et al. 2016). Carbon dioxide absorbed by oceans reacts with seawater forming carbonic acid and thus making seawater more acidic. Over the past 150 years, acidity has increased by 26 percent, reducing ocean pH by 0.1 pH units (Hoegh-Guldberg et al. 2017). As the acidity of seawater increases, the ability of corals, shellfish and other marine organisms to build their skeletons and shells declines (Orr et al. 2005; Doney et al. 2009). Calcification of the massive coral *Porites* on the Great Barrier Reef has been declining since at least 1990 (De'ath et al. 2009; D'Olivo et al. 2013) and ocean acidification combined with elevated warming and decreased water quality seem to be the main drivers. If carbon dioxide emissions are not rapidly reduced, coral reefs may shift into a state of net dissolution by the end of this century (Hoegh-Guldberg et al. 2007; Silverman et al. 2009; Ricke et al. 2013).

Ocean acidification can also interfere with the development, reproduction and homing ability of fish. For instance, ocean acidification has been shown to interfere with the processing of sensory information in larval fish, attracting them to irrelevant cues for settlement or leading them to ignore relevant cues. Other experiments have found that clownfish larvae raised under elevated carbon dioxide were attracted to the odours of unsuitable habitats (Munday et al. 2009) and barramundi larvae were attracted to the sound of unsuitable habitat or white noise from humans instead of the sounds of tropical estuarine mangroves, which is their ideal habitat (Rossi et al. 2018). Changes to ocean chemistry thus have the potential to significantly influence the population replenishment of fish because the longer fish larvae take to settle in suitable habitat, the greater the risk of mortality from predation or starvation.

Figure 11: Ocean acidification can interfere with the sensory perceptions of fish, causing them to be attracted to the odours and sounds of unsuitable natural habitats or white noise from humans.

6. Woefully inadequate Federal Government response to the Great Barrier Reef's biggest threat

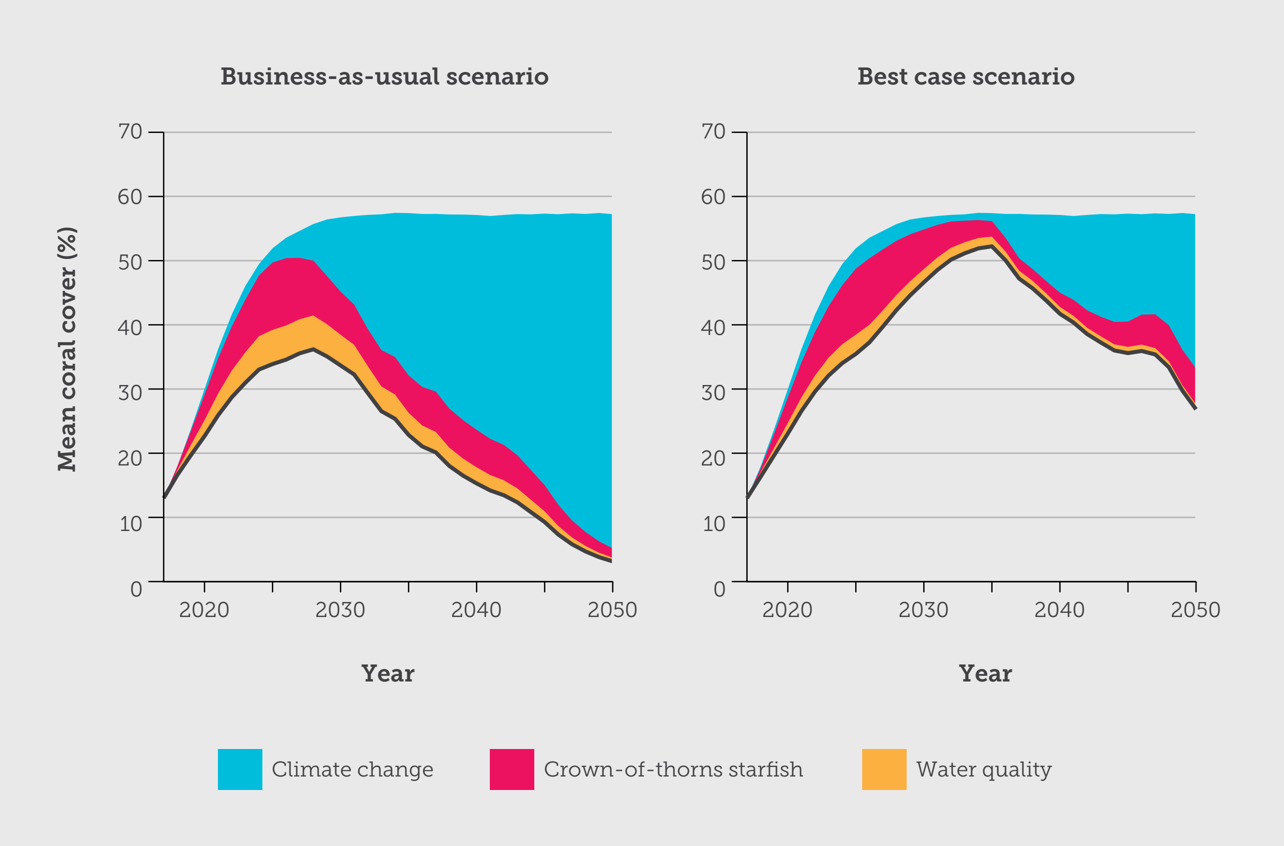
The Turnbull Federal Government has recently announced funding of $535.8 million over five years from 2017-2018 to 2021-2022 to improve the resilience of the Great Barrier Reef.

These funds will be directed towards improving water quality through reducing sediment run-off from agriculture ($200.6 million), tackling the crown-of-thorns starfish ($58 million), research on reef restoration ($100 million), community engagement ($44.8 million) and reef monitoring ($40 million) (Parliament of Australia 2018). Yet funding for addressing the greatest threat to coral reefs – climate change – was reduced in the 2018 budget, from $3 billion in 2018 to $1.6 billion in 2019, and it will be further cut to just $1.25 billion by 2022 (Commonwealth of Australia 2018; SMH 2018). Whilst sediment run-off and the crown-of-thorns starfish place additional stress on an already stressed system, there is scant evidence that local management can sufficiently reduce susceptibility of corals to bleaching from marine heatwaves in the long-term (Wolff et al. 2018). Without effectively addressing climate change, the Federal Government's plan will not help protect the Great Barrier Reef.

The relative impact of nutrient run-off, crown-of-thorns starfish, cyclones and climate change on the Great Barrier Reef has been modelled by Wolff et al. (2018) to investigate the potential for local management to reduce the future vulnerability of the Great Barrier Reef through 2050. Across all six scenarios, capturing different combinations of climate change and local management actions, this study found potential for coral recovery in the next 10 to 20 years relative to current historic low Great Barrier Reef coral cover. However, this period of potential recovery, with peaks between 2020 and 2035 depending on the scenario, is followed by declines through 2050, with climate change being the primary factor determining the steepness and extent of the decline.

Under a business-as-usual scenario, where greenhouse gas pollution continues unabated and local stressors remain constant, mean coral cover is projected to decline to approximately 5 percent by 2050, with 72 percent of the decline attributable to climate change (see Figure 12). Under a scenario where local management is improved and global average temperature rise is limited to no more than 1.5°C (the best case scenario), mean coral cover is projected to decline from 2035 peak values to approximately 30 percent by 2050, with 54 percent of the decline attributable to climate change.

Figure 12: Business as usual (left) and best case scenario (right) for the Great Barrier Reef. The blue area represents loss due to global warming (bleaching), the magenta area the loss due to crown-of-thorns starfish, the yellow area the loss due to poor water quality and the grey line represents coral cover when all disturbances are present (adapted from Wolff et al. 2018).



Local management solutions can only contribute to reducing the vulnerability of the Great Barrier Reef if combined with deep cuts to greenhouse gas pollution, commensurate with limiting global average temperatures to 1.5°C above pre-industrial levels.

The authors of this study acknowledge that predictions of future coral cover are indicative only, and that the relative contribution of climate change impacts versus local impacts on reef degradation may be underestimated because the effects of ocean acidification and potential intensification of tropical cyclones on the Great Barrier Reef are not included in the modelling.

There is little evidence that coral populations will be able to acclimatise, adapt or shift fast enough to withstand increasing sea surface temperatures. Ocean isotherms (lines connecting points of similar temperatures on a map) have been shifting at a rate of around 200 km per decade between 1960 and 2010 in equatorial regions. Around the Great Barrier Reef ocean isotherms have been shifting at a rate of 50-100 km/decade (Burrows et al. 2011; 2014). By contrast, populations of individual coral species have been shifting at an average rate of only 30 km per decade, too slow to keep up (Poloczanska et al. 2013; Hoegh-Guldberg 2012; Burrows et al. 2014; Garcia Molinos et al. 2015).

Evidence that corals can acclimatise by developing resistance to heat from previous exposure is similarly limited, with corals on the Great Barrier Reef that were exposed to past bleaching from marine heatwaves in 1998 and 2002 shown to be just as susceptible to bleaching in 2016 (Hughes et al. 2017).

Only 3 percent of the Great Barrier Reef (roughly 100 reefs) has been identified as having the ideal properties to facilitate recovery and replenishment of other disturbed areas (Hock et al. 2017). Targeting local conservation efforts towards these reefs therefore makes sense. However, localised activities can only offer limited and short-term help.

Even under the most optimistic emission reduction scenarios, mass coral bleaching events can be expected to increase (Frieler et al. 2013; Ortiz et al. 2014). Under current greenhouse gas pollution rates, the extreme ocean temperatures that led to the 2016 and 2017 bleaching events may occur every two years by 2034 (CoECSS 2016). Such a short period between bleaching events is not sustainable as coral reefs take at least a decade to fully recover (Hughes et al. 2018b). Furthermore, ocean acidification will increasingly undermine the processes that sustain reef resilience by reducing the ability of corals to develop and maintain their skeletons.

7. What can be done to protect coral reefs?

Limiting temperature rise above pre-industrial levels to no more than 1.5°C is critical for the survival of at least some reefs worldwide (Frieler et al. 2013; Schleussner et al. 2016). A global average temperature increase of 1.5°C above pre-industrial levels would put 70 percent of coral reefs at risk of long-term degradation by 2100 and a rise of 2°C would put 99 percent of coral reefs at risk (Schleussner et al. 2016).

The impacts of different emissions scenarios on coral trajectories becomes increasingly apparent as time progresses. Beyond 2050, the difference between a global average temperature rise of 2°C or 1.5°C above pre-industrial levels is dramatic. Under a scenario where temperature rise is limited to 2°C, Wolff et al. (2018) project that the Great Barrier Reef would collapse by 2070. By contrast, under a scenario where warming is limited to 1.5°C, they project that coral cover would increase in the near term, decline significantly between 2035 and 2050 then recover between 2060 and 2100 (Wolff et al. 2018).

There is still hope for the Great Barrier Reef in the long-term. But our actions now will determine its long-term survival and that of all warm-water coral reefs around the world. It is imperative that global average temperature rise does not exceed 1.5°C above pre-industrial temperatures.

To have a chance of achieving this, global greenhouse gas emissions must peak by 2020 at the latest and track steeply downwards thereafter, reaching net zero emissions by 2050 at the latest. For Australia, this means rapidly replacing our ageing and inefficient coal and gas fired power stations with renewable energy and storage, electrifying transport powered by 100 percent renewable energy and leaving fossil fuels in the ground. The Federal Government's current proposed policy to address climate change – the National Energy Guarantee – has an emissions reduction target of just 26-28 percent below 2005 levels by 2030, nowhere near what is required to do our fair share to limit global temperature rise to 1.5°C.

Time is running out rapidly. Australia is the custodian of the Great Barrier Reef, one of the seven natural wonders of the world. We have an obligation to lead global efforts to restore and protect the reef. It's time to ramp up our climate policies and actions, getting on with the job of cutting our greenhouse gas pollution and accelerating the transition away from coal to renewable energy.

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