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Important Information

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DISTINGUISHED PROFESSOR TERRY HUGHES FAA

[redacted]

[redacted]

28 April, 2023

I have prepared this report in response to an expert brief provided to me by Phi Finney McDonald who are acting on behalf of Pabai Pabai and Guy Paul Kabai.

I have been asked to prepare an expert report in relation to the impacts of anthropogenic climate change on coastal and marine ecosystems in the Torres Strait region.

ANNEXURE A is the letter of instruction provided to me by Phi Finney McDonald.

ANNEXURE B is the supplementary letter of instruction provided to me by Phi Finney McDonald.

ANNEXURE C is a list of figures referred to in my report.

My relevant qualifications are included below in the form of an abbreviated CV (Annexure D). It details my tertiary academic qualifications, employment history, a list of my published works, and a brief statement of my expertise.

I acknowledge that I have been provided with, read, complied with and agree to be bound by the Federal Court of Australia Expert Evidence Practice Note (GPN-EXPT) and Harmonised Expert Witness Code of Conduct.

My opinions in this report are based wholly or substantially on specialised knowledge arising from my training, study or experience.

I have made all the inquiries which I believe are desirable and appropriate (save for any matters identified explicitly in this report) and confirm that no matters of significance which I regard as relevant have, to my knowledge, been withheld from the Court.

Yours Sincerely

Terence Hughes

Terry Hughes

27/04/2023

I. BASIS OF EXPERTISE

Question 1

Please describe your academic qualifications and professional background, your experience in the field of climate change impacts to marine life (including, in particular, in the Torres Strait) and any other training, study or experience that is relevant to this brief. You may wish to do so by reference to a current curriculum vitae.

1) A listing of my academic qualifications, professional background, employment history, and expertise in the field of climate change impacts on marine life (including in Torres Strait) is provided in an abbreviated curriculum vitae comprising ANNEXURE D.

2) Briefly, I have received a PhD and three honorary DScs for my research on the ecology and evolution of marine ecosystems. My publications have been cited more than 89,000 times in the scientific literature. I am a Fellow of the *Australian Academy of Science* (elected 2001) and of the *Beijer Institute for Ecological Economics* (since 2006) at the *Royal Swedish Academy of Sciences*. I have received numerous international awards in recognition of my research, including the 2018 Climate Change Award from Prince Albert II of Monaco. In February 2020, I was awarded a *Frontiers of Knowledge Award* from the BBVA Foundation, in Spain, for my lifetime contributions to marine ecology and climate change research.

3) I have conducted extensive marine fieldwork in the Caribbean (e.g. Jamaica, Panama, Tobago), throughout the tropical Pacific (principally Australia, French Polynesia, Indonesia, PNG, Samoa, Solomon Islands), including in Torres Strait (since 1994). In 2016, 2017 and 2020, I led the research response to mass coral bleaching and losses of corals throughout the Great Barrier Reef and Torres Strait.

4) My professional background includes advisory roles to IUCN, UNESCO, multiple environmental NGOs, Science Academies, and many appointments to government committees and advisory boards in Australia and elsewhere.

II. CLIMATE SCIENCE ASSUMPTIONS

For the purposes of your answers to the questions below, please assume that the following matters are impacted by climate change:

i) global average surface temperature (calculated from both land and ocean temperatures); ii) ocean surface temperature; iii) ocean acidification; iv) rising sea levels; and v) the frequency, size and intensity of extreme weather events, including heatwaves, droughts, tropical cyclones, severe storms and heavy rainfall (as well as associated flooding) (together, "Climate Impacts").

Climate Change and its Components

5) Anthropogenic climate change, primarily due to burning of fossil fuels, has already affected marine and coastal ecosystems throughout the tropical oceans. Climate change has four main components or elements (referred to in the question above as "Climate Impacts") that affect people and ecosystems:

    a) Gradually rising land and sea temperatures. Higher temperatures alter the physiology, metabolism, reproduction and growth rates of animals, plants and microbes, and where they can survive. Global average temperatures have already risen by approximately 1.2^{o}C in the past century.

    b) Ocean acidification and changes in water chemistry. The ocean has absorbed roughly one third of the anthropogenic carbon dioxide emissions over the past century. Shallow-water pH and aragonite saturation states, which are critically important for calcification and other processes in the ocean, will continue to drop as atmospheric CO_2 rises. The global average pH of ocean surface waters has declined over the past 100 years by approximately 0.1 units, from 8.2 to 8.1, causing a reduction in coral growth and calcification rates (De'Ath et al. 2009). Ocean acidification in the tropics is unfolding more slowly than other climate change components. Consequently, its impacts on tropical ecosystems such as the Great Barrier Reef have been comparatively small compared to ocean warming and heatwaves.

    c) Rising sea levels, due predominantly to thermal expansion and melting land ice. Sea level rise primarily affects coastal and other shallow-water ecosystems. For example, intertidal species and habitats, including mangroves, coral reef flats and nesting turtles, are particularly vulnerable to inundation and rising sea levels in coming decades. Sea level rise also increases the risks of coastal inundation and salinization of wetlands.

    d) Increased variability and climatic instability, including more extreme and prolonged marine heatwaves, cyclones, droughts, coastal floods and runoff of sediment and nutrients. Spikes in sea temperature during increasingly hot summers produce destructive episodes of mass coral bleaching that, by definition, extend over very large areas. Compared to the longer timeline for significant sea level rise and ocean acidification, extreme heatwaves are already causing severe damage to marine species and ecosystems at a global scale.

6) This report focusses on the current (and the projected near-future) impacts of these four components of anthropogenic climate change on tropical marine species and ecosystems. Each is occurring simultaneously, and they are highly interactive. For example, gradual sea level rise exacerbates local coastal inundation during storm surges. Similarly, ongoing anthropogenic heating at a global scale slowly raises the baseline above which summer spikes in temperature occur during regional-scale heatwaves.

Torres Strait

7) Torres Strait extends for 150km north of Cape York Peninsula towards the coastline of Papua New Guinea, and for up to 300km east-west, encompassing an area of approximately 48,000km^2. Close to 9,500 people live on 17 of the 300 islands in the region (TSRA 2021). Torres Strait culture (Ailan Kastom) and livelihoods are deeply linked to land and sea country. The four main categories of islands in Torres Strait each support distinctive ecosystems and species - continental islands in the west, central and eastern coral cays, offshore volcanic islands predominantly in the east, and muddy alluvial islands in the north. Biologically and geologically, Torres Strait is the northernmost part of the Great Barrier Reef.

8) Many key elements of the fauna and flora of the region move freely across the political and jurisdictional boundaries that separate Torres Strait, coastal PNG to the north, the Coral Sea to the east, The Arufa Sea to the west, and the Great Barrier Reef World Heritage Area (or World Heritage "property") to the south. For example, many species of seabirds, the dugong, turtles, and sharks migrate seasonally across and beyond these boundaries. Similarly, the juvenile propagules of sessile species (e.g. seeds of mangroves and sea grasses, and the larvae of many fishes and invertebrates) disperse out of and into Torres Strait.

9) Torres Strait ecosystems are also strongly influenced by physical connections to neighbouring regions - including runoff of sediment, nutrients and pollutants from mainland rivers in PNG and Cape York Peninsula, upwelling of relatively cool oceanic water at the interface with the Coral Sea, and strong currents connecting the Arufa and Coral Seas. This high degree of connectivity or connectedness is important for understanding the condition and trends in the Outstanding Universal Value (**OUV**) of the entire region. "Connectivity", "Intactness", "Integrity" and OUV are key inter-related concepts used by the Commonwealth government, UNESCO and IUCN to describe the state of the Great Barrier Reef World Heritage Area (or property) since 1981 (State Party Report 2014, GBR Outlook Report 2019, IUCN World Heritage Outlook 2020). This report adopts this framework in relevant sections to examine the current and near-future state of OUV in Torres Strait.

10) To be included on the World Heritage List, sites must be of Outstanding Universal Value (OUV) and meet specific criteria for listing. UNESCO defines OUV as cultural or natural attributes of a site that are exceptional, superlative, and globally significant. The four natural criteria invoked for World Heritage listing of the Great Barrier Reef in 1981 were:

(1) significant geomorphic features

(2) significant ongoing ecological and biological processes

(3) significant natural habitats for the conservation of biological diversity, and

(4) exceptional natural beauty.

11) Each of these criteria is measured and monitored over time, and reported annually to UNESCO. Australia measures 38 quantitative metrics of OUV, and a further 3 metrics to record and track trends in Integrity (Table 1).

12) The most explicit account of the decline in world heritage values of the Great Barrier Reef is included in Australia's reporting to UNESCO in its 2014 State Party Report, in Appendix 3—*Benchmarking the Outstanding Universal Value of the Great Barrier Reef World Heritage Area* (summarized in Table 1). These reported declines occurred in 46-75% of the values comprising each of the four criterion, and they pre-date the substantial further impacts of record high temperatures in 2016, 2017, 2020 and 2022.

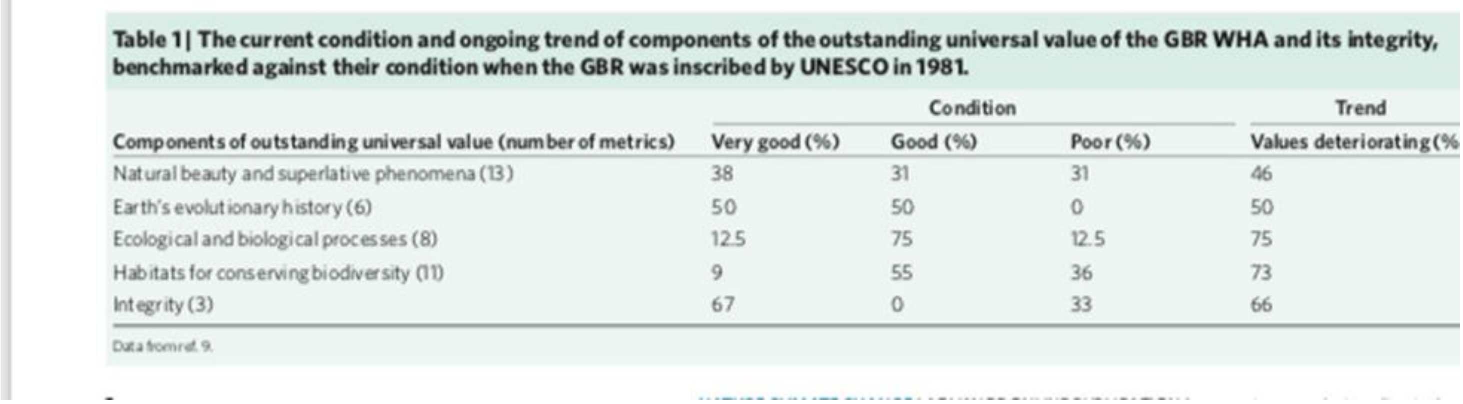

Table 1| The current condition and ongoing trend of components of the outstanding universal value of the GBR WHA and its integrity, benchmarked against their condition when the GBR was inscribed by UNESCO in 1981.

	Condition			Trend
Components of outstanding universal value (number of metrics)	Very good (%)	Good (%)	Poor (%)	Values deteriorating (%
Natural beauty and superlative phenomena (13)	38	31	31	46
Earth's evolutionary history (6)	50	50	0	50
Ecological and biological processes (8)	12.5	75	12.5	75
Habitats for conserving biodiversity (11)	9	55	36	73
Integrity (3)	67	0	33	66

Data from ref. 9.

Table 1. The condition (very good, good or poor) and ongoing trend of components of the Outstanding Universal Value of the Great Barrier Reef World Heritage Area and its Integrity, benchmarked against their condition when the Great Barrier Reef was inscribed by UNESCO in 1981. Adopted from the State Party Report (2014). (Hughes et al. 2015).

13) Torres Strait was not included within the Great Barrier Reef Marine Park when the Park as initiated in 1976. Similarly, Torres Strait was excluded from the inscription of the Great Barrier Reef World Heritage Area in 1981. In its latest 5-yearly Great Barrier Reef Outlook Report (2019), the Commonwealth describes the jurisdictional scope of the Outlook report as covering the "entire Great Barrier Reef Region" (Figure 1), which they define as follows:

> *"The Region is a Commonwealth jurisdiction covering approximately 346,000 square kilometres, from the tip of Cape York in the north to past Lady Elliot Island in the south, with mean low water as its western boundary and extending eastwards a distance of between 70 and 250 kilometres to the eastern border with the Coral Sea Marine Park.* ***It excludes the Torres Strait Region.*** *.....The State of Queensland has jurisdiction over the majority of islands in the Reef (approximately 980 islands) which are, therefore,*

> *not included formally within the Region. However, where it is relevant to the health of, or factors influencing, the Great Barrier Reef ecosystem and its heritage values, the report looks beyond the Region's boundaries and includes information about adjacent islands, neighbouring marine areas and the Great Barrier Reef river catchments (the Catchment)."* (GBRMPA 2019).

14) Despite this formal exclusion, the Commonwealth's three Great Barrier Reef Outlook Reports (2009, 2014 and 2019) do include a substantial amount of information about Torres Strait, while also acknowledging the critical role of Aboriginal and Torres Strait Islanders in stewardship of these iconic ecosystems. The Aboriginal and Torres Strait Islander Heritage Strategy for the Great Barrier Reef Marine Park (GBRMPA 2019b) describes the objectives and outcomes for managing the Region's Indigenous heritage value.

Figure 1. Map of the Great Barrier Reef Marine Park and World Heritage Area, and the adjoining catchment. Although Torres Strait is formally considered by the Commonwealth to be outside of the Great Barrier Reef Region, Torres Strait is

ecologically and geologically inseparable from the rest of the Great Barrier Reef (GBR Outlook Report 2019).

15) Indigenous and historical values were not considered in the 1981 inscription of the Great Barrier Reef as a World Heritage Area. The Great Barrier Reef (excluding Torres Strait) has been placed since 2007 on the Commonwealth's National Heritage List, together with all other existing Australian World Heritage sites. Heritage values of the Great Barrier Reef Region were considered in the Great Barrier Reef Outlook Report in 2014, following amendments in 2008 to the Great Barrier Reef Marine Park Act 1975 (Cth). The scope of the assessments in the 2014 and 2019 Outlook Reports includes the Great Barrier Reef Region's natural (biological and geological), Indigenous, and historic heritage value (e.g. ship wrecks, lighthouses), excluding Torres Strait.

16) The two most relevant Commonwealth agencies for the Great Barrier Reef are the Great Barrier Reef Marine Park Authority (GBRMPA) and the Australian Institute of Marine Science (AIMS). Reef management and zoning, poaching surveillance, culling of crown-of-thorns starfish, and other activities undertaken by GBRMPA, and the extensive Long-Term Monitoring Program of the Great Barrier Reef conducted annually by AIMS since 1983, are largely restricted to the Marine Park. (In 2022, these two agencies included Torres Strait in their aerial surveys of mass coral bleaching along the full length of the Great Barrier Reef).

17) Torres Strait Regional Authority (TSRA) is a Commonwealth statutory body established in 1994 to represent the interests of Torres Strait Islander and Aboriginal people. TSRA, GBRMPA and AIMS report to three different Commonwealth Ministers. TSRA has produced two State of the Environment Reports, in 2016 and 2021. The 2021 report states "*There are many aspects of the region for which there is little or no recorded scientific information. Future investment will be required to address critical gaps in understanding about the biocultural land and seascapes of Torres Strait for improved environmental outcomes*" (TSRA 2021).

18) The jurisdictional separation of Torres Strait from the Great Barrier Reef Marine Park, and later from the Great Barrier Reef World Heritage Area, has constrained Commonwealth resourcing for research, monitoring and environmental management over the past 5 decades. A parallel but separate set of environmental monitoring and reporting is still developing in Torres Strait. This institutional arrangement has consequences for this report because of the disparity in the amount of information available from Torres Strait compared to more intensively monitored sections of the Great Barrier Reef that are closer to research hubs in Cairns, and in Townsville (where AIMS, GBRMPA and James Cook University are headquartered).

19) The *Reef 2050 Long-Term Sustainability Plan* provides a framework and more than a billion dollars in projected funding for management of the Great Barrier Reef World Heritage Area (again, excluding Torres Strait) in coming decades. The Plan was initiated by the Commonwealth and State of Queensland at the request of UNESCO, in response to growing evidence from the Great Barrier Reef Outlook Reports that the World Heritage Area is in decline. The majority of the Plan focusses on achieving targets for reducing

inshore water pollution due to terrestrial runoff. However, the Plan has no targets for reducing greenhouse gas emissions, the number one threat to Torres Strait and to the Great Barrier Reef's World Heritage values, as identified in all three of the Commonwealth's Great Barrier Reef Outlook reports (2009, 2014 and 2019).

20) As part of its role as scientific advisor to UNESCO, the International Union for the Conservation of Nature (**IUCN**) produced three World Heritage Outlook reports for the Great Barrier Reef World Heritage Area, in 2014, 2017 and 2020 https://worldheritageoutlook.iucn.org. These reports are based on the peer-reviewed scientific literature, the Commonwealth's Great Barrier Reef Outlook Reports, and the annual State Party reporting by Australia to UNESCO. The first and second IUCN reports rated the Great Barrier Reef World Heritage Area as of 'Significant concern'. IUCN's latest 2020 report downgraded the Great Barrier Reef's Conservation Outlook to "Critical". The present report assesses parallel trends occurring in Torres Strait (especially Question 7).

21) Integrity and many elements of World Heritage Values of the Great Barrier Reef have slowly eroded since inscription, for example, the depletion of megafauna and seabirds, and the episodic loss of corals due to anthropogenic heating (Table 1). While there have been moderate improvements in water quality in some river catchments, many of the values of the Great Barrier Reef continue to be seriously damaged by coastal pollution and by ongoing climate change (Great Barrier Reef Outlook Report 2009, 2014, 2019).

22) Following the third and fourth episode of mass coral bleaching in 2016 and 2017, the Commonwealth's third (2019) Great Barrier Reef Outlook Report noted "*While the property's outstanding universal value as a World Heritage Area remains whole and intact, its Integrity is challenged and deteriorating. Given the global scale of human-induced climate change, the size of the property is becoming a less effective buffer to broadscale and cumulative impacts. Attributes that remain in good condition at a Region-wide scale include the spectacular scenery, over half of the ecosystem processes, and some species components.... At a Region-wide scale, ecosystem processes have not ceased to operate. However, ecological and biological processes that are fundamental to a functioning ecosystem (for example, reef building, recruitment and symbiosis) are considered to be in poor condition"* (Section 4.2.4, p. 89). The same conclusion applies to Torres Strait, as documented throughout the present report.

III. CLIMATE IMPACTS

2. *Please identify and explain the relationship between the Climate Impacts and the following aspects of marine life:*

(a) *Mangroves and coastal wetlands;*

23) In Question 2, I address the effects of Climate Impacts (the four components of climate change, described in paragraph 5) on multiple aspects of coastal marine life in the tropics. For the purposes of this report, the six biological responses, 2(a)-(f), to Climate Impacts are collectively termed "Marine Life Impacts". Questions 4 to 7 address marine life responses to Climate Impacts specifically in Torres Strait ("Torres Strait Impacts"). For part (a) I have included seagrass ecosystems, because coastal wetlands, mangroves, intertidal and subtidal seagrasses commonly occur together in the tropics along an inshore-offshore gradient. The terms coastal wetlands and mangroves are often used interchangeably, although the former can also refer to saltpans, brackish swamps, and other types of vegetation. All three of these ecosystems are particularly vulnerable to Climate Impacts, including acute heat stress, drought, floods, severe storms, sea level rise and coastal inundation. These climate change components reinforce each other, and their combined impacts on coastal wetlands, mangroves and seagrasses are often exacerbated by local pressures, including water pollution, clearing of mangroves and wetlands for farming, aquaculture, and coastal development.

24) In the summer of 2015-16, one of the most catastrophic mangrove diebacks ever recorded globally occurred in the Gulf of Carpentaria. A combination of extreme heat, prolonged drought and anomalously low sea levels (due to the 2015-2016 El Niño event) caused the unprecedented mass mortality of 40 million mangrove trees across more than 2,000 kilometres of coastline. The die-off released nearly 1 million tonnes of carbon (Duke et al. 2022). This event initially went unnoticed for many months, highlighting the disparity in monitoring of marine ecosystems in remote locations compared to the intensity of management of the Great Barrier Reef Marine Park. Recovery so far has been slow - two severe cyclones affected the Gulf of Carpentaria coast in 2018 and 2019.

25) Similarly, an intense marine heatwave in Shark Bay, Western Australia, in 2010/2011 killed an estimated 36% of one of the largest seagrass ecosystems in the world, over an area of 1,100km^2 (Arias-Ortiz et al., 2018). The die-off was initiated when Sea Surface Temperatures rose by 2˚C-4˚C above the long-term average summer maximum, for more than two months. Severe bleaching and mortality of corals was also recorded at the same time. Afterwards, water clarity decreased due to loss of sediments, and widespread blooms of phytoplankton and bacteria were triggered by released nutrients. The food-web connecting seagrasses, herbivorous dugong and green turtles, and apex predator tiger sharks were widely disrupted. This example of a seagrass die-off released an estimated 2–9 million tonnes of CO_2 (Arias-Orrtiz et al. 2018). While Blue Carbon (storage of carbon in mangroves and sea grasses) is often presented as a "nature-based solution" to climate change, these two examples illustrate the vulnerability of these ecosystems to further anthropogenic warming.

26) Sea-level rise is already damaging nearshore ecosystems habitats, such as mangroves, mudflats and beaches, coastal wetlands and sea grasses, and intertidal coral reefs. Future sea-level rise and higher temperatures may also exceed the adaptive capacity of subtidal ecosystems, including seagrasses and coral reefs, especially if they are also stressed by more local anthropogenic impacts (e.g. coastal pollution, runoff of sediment during flood events). The biodiversity and mix of species (species composition) of all types of marine ecosystems is already changing rapidly due to differences in susceptibility to heat stress among species, and to differences in their capacity to rebound between recurrent temperature extremes and other climate-related disturbances. Nesting marine turtles and birds are particularly vulnerable to loss of rookeries from sea level rise, and to the impacts of rising temperatures on the gender ratio of hatchlings (Jensen et al. 2018). (Biodiversity and vulnerability of species and ecosystems to climate change is also described in Question 2(d) and (e)).

27) In the recent geological past (at the end of the last ice age), shallow marine ecosystems along the Great Barrier Reef and elsewhere migrated onto inundated coastlines as sea levels rose and continental shelves were flooded. Sea-level remained relatively stable for the past 6000 years, prior to anthropogenic heating. However, today coastwards migration in response to anthropogenic sea level rise is often impeded by physical barriers, including roads, buildings and marine infrastructure. Low-lying island (e.g. coastal wetlands and coral cays in Torres Strait) are already facing inundation and erosion from contemporary sea-level rise and severe weather, directly threatening coastal [redacted] ecosystems.

(b) *Coral bleaching events*

28) Large-scale coral bleaching is caused by very high sea temperatures, especially during unprecedented heatwaves. In part (b), I have also included a summary of the current and projected near-future impacts of ocean acidification on corals. Of the four components of Climate Impacts, three are critically important for coral reefs - rising temperatures, extreme weather including heatwaves, and ocean acidification. Coral bleaching occurs when the relationship between corals and the photosynthetic symbionts that live inside their tissues breaks down, turning the coral pale. Bleaching can be triggered in the laboratory by exposing corals to stress, such as hot or cold temperatures, high or low salinity, or by exposing them to sediment and other pollutants.

29) In nature, bleaching historically occurred infrequently at local scales in response to severe weather and cyclones, or to an influx of low salinity water and sediment on coastal fringing reefs adjacent to rivers. In the past four decades, coral bleaching has increased in frequency, severity and spatial scale due to anthropogenic heating. Bleached corals are physiologically damaged and nutritionally compromised, and corals often die when bleaching is severe (Fig 2).

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Figure 2. Anthropogenic heating has emerged as a global threat to coral reefs, following the first pan-tropical event in 1998. This image, from the far northern Great Barrier Reef in 2016, shows close to 100% mortality of corals due to heat exposures of >12 Degree Heating Weeks. Most of the dead corals are staghorn and tabular species of *Acropora*, which are dominant corals in Torres Strait. (Hughes et al. 2018).

30) The relationship between bleaching intensity and subsequent mortality of corals is well established (Figure 3): when bleaching is mild (affecting less than 20% of corals), most corals regain their colour after a few weeks and survive. In contrast, when bleaching is severe (affecting >20% of corals) most of the bleached corals subsequently die (Figure 3).

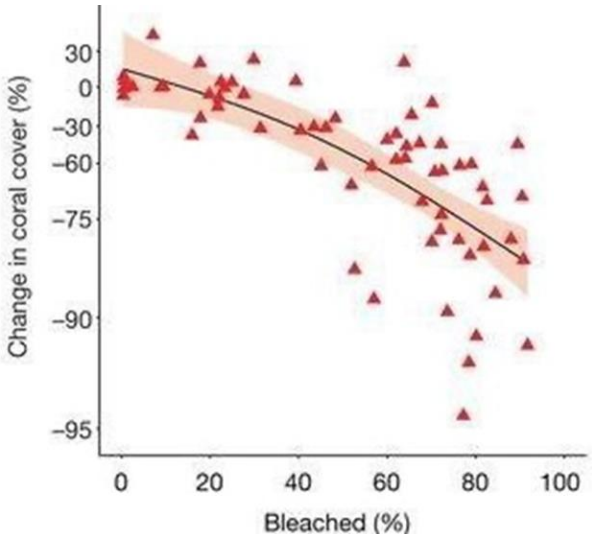

Figure 3. The relationship between the severity of bleaching and subsequent loss of corals ($\log_{10}$ scale) on the Great Barrier Reef and Torres Strait in 2016. Each data-point represents an individual reef (Hughes et al. 2018).

31) Mass bleaching of corals is a modern phenomenon due to anthropogenic heating that causes longer and more extreme heatwaves (Oliver et al. 2009, Lough et al. 2018). Already, with approximately 1.2°C of average global warming above pre-industrial temperatures, coral reefs have experienced three pan-tropical episodes of intense coral bleaching in the past three decades (in 1997-8, 2010 and 2015-2016). 1998 was (then) the warmest year since modern temperature records began. Each of these unprecedented events affected at least half of the world's reefs. Figure 4 shows the geographic extent of mass coral bleaching in the most recent 2015-2016 global event.

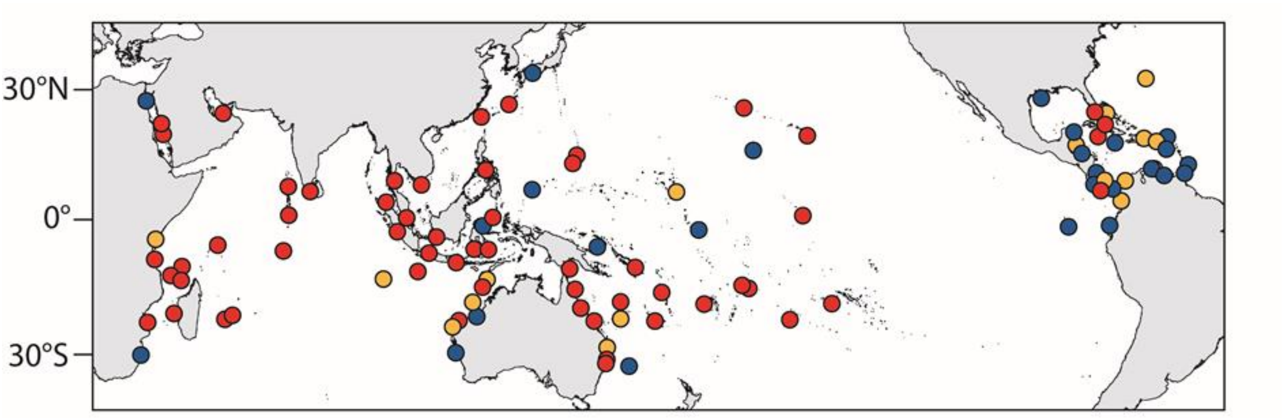

Figure 4. The geographic extent of the 3rd and most recent pan-tropical mass-bleaching of corals, in 2015-2016. Circular symbols show 100 reef locations that were assessed: red – severe bleaching affecting >30% of corals; orange – moderate bleaching affecting <30% of corals; blue circles – no significant bleaching recorded. (Hughes et al. 2018).

32) The severity of bleaching depends on the height of a spike in temperature (measured as a positive temperature anomaly in degrees Centigrade, relative to the long-term historical average) and its duration (usually measured in weeks). Corals are sensitive to temperatures

warmer than 1°C above the average summertime maximum (i.e. an anomaly of +1ºC). Consequently, measurements of heat stress and seasonal forecasts of coral bleaching (issued by the US National Oceanic and Atmospheric Administration (NOAA) and the Australian Bureau of Meteorology) are based on the Degree Heating Week (DHW) thermal stress metric, a widely-used measure that incorporates both the duration and intensity of heat exposure each summer. DHW measures how far the temperature is above the +1ºC threshold that triggers mild bleaching, and how long it stays above that threshold. For example, the same DHW exposure can arise from a long moderate heatwave as a short-lived extreme peak in temperatures. "Normal" temperatures that are lower than one degree above the longstanding summer maximum do not contribute to measurements of DHW. DHW is measured most commonly from satellites, producing high-resolution maps of observed and predicted heat exposure at a global scale (Liu et al. 2014). The observed relationship between DHW and the severity of coral bleaching on the Great Barrier Reef Marine Park and Torres Strait in 2016 is shown in Figure 5.

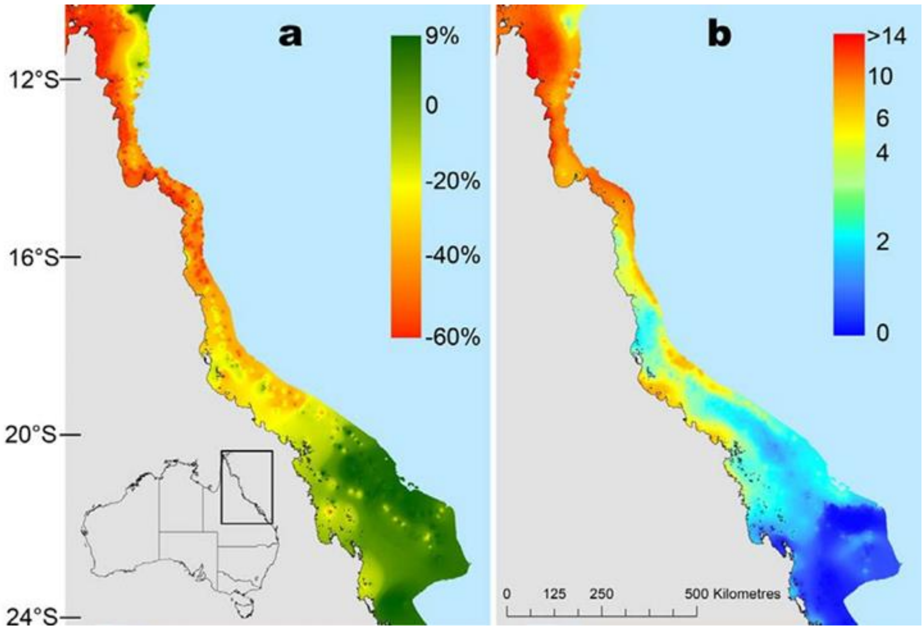

Figure 5. Large-scale spatial patterns in change in coral cover and in heat exposure on the Great Barrier Reef, Australia. (a) Change in coral cover between March and November 2016. (b) Heat exposure, measured as Degree Heating Weeks (DHW, ºC-weeks) in the summer of 2015/2016. Heat exposure and subsequent losses of corals was highest in Torres Strait (Hughes et al. 2017a).

33) Severe mass bleaching causes widespread mortality of corals at unprecedented scales, far exceeding the damage caused by a severe cyclone (Dietzel et al. 2021a). For example, in 2016, the total cover of shallow-water corals on the Great Barrier Reef declined by 30.0% between March and November (Hughes et al. 2018b, Great Barrier Reef Outlook Report 2019). This loss, of billions of corals, was unmatched in scale and severity.

34) Increasingly, climate-driven bleaching is occurring in all El Niño Southern Oscillation (ENSO) phases, because as global warming progresses, average tropical sea surface temperatures are warmer today under La Niña conditions than they were during El Niño events only three decades ago (Hughes et al. 2018a). Since 1980, 58% of severe bleaching events throughout the tropics have been recorded during four strong El Niño periods (in 1982-1983, 1997-1998, 2009-2010 and 2015-2016), with the remaining 42% occurring during hot summers in other ENSO phases. Inevitably, the link between El Niño as the predominant trigger of mass bleaching is diminishing as global warming continues, and as summer temperature thresholds for bleaching are increasingly exceeded throughout all ENSO phases.

35) Prior to 1998, then the hottest year on record, coral bleaching was rare and localized because sea temperatures were cooler than those experienced today, including during historical El Nino periods (Oliver et al. 2009). Sea surface temperatures on the Great Barrier Reef in December 2021 – at the beginning of the most recent mass bleaching event - were the hottest recorded by the Australian Bureau of Meteorology since their measurements began in 1900. Figure 6, produced by the Australian Bureau of Meteorology, shows the clear warming trend in sea surface temperatures on the Great Barrier Reef over the past 120 years.

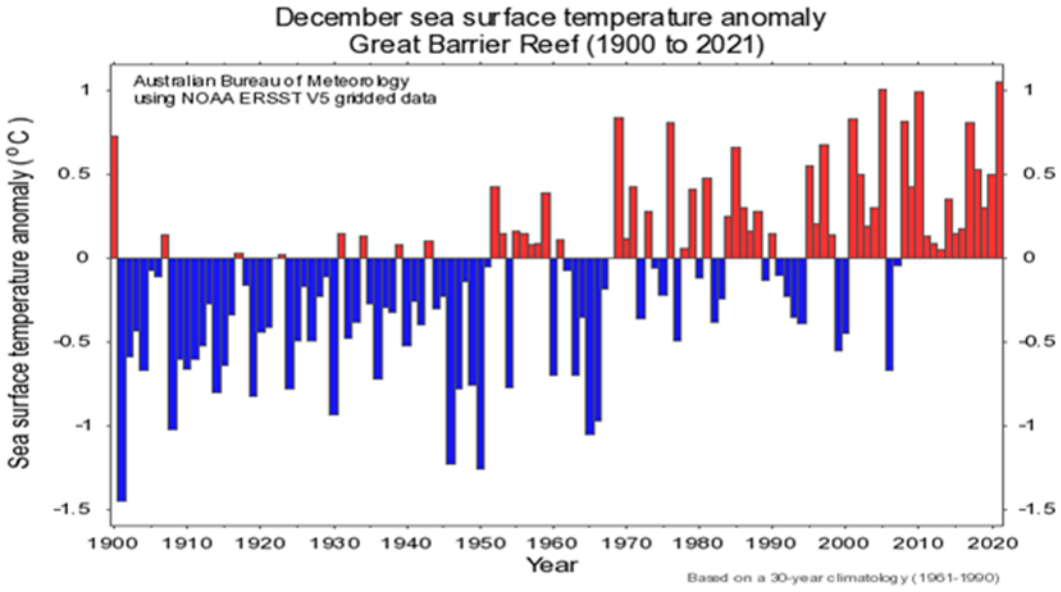

Figure 6. Sea surface temperature anomalies on the Great Barrier Reef in December, 1900-2021. Blue bars indicate years where temperatures were lower than the 1961-1990 reference period. Red bars indicate warmer, positive anomalies. (Australian Bureau of Meteorology, 2022).

36) The Great Barrier Reef as a whole has experienced mass coral bleaching six times in the past 24 years due to global heating, in 1998, 2002, 2016, 2017, 2020, and 2022. Two of these events coincided with El Nino conditions (1998 and 2016), and the remaining four did not. Sea surface temperatures (SSTs) during El Nino summers are slightly warmer in

most parts of the tropical Ocean. However, due to anthropogenic heating, average SSTs during cooler La Ninas are now hotter than they used to be 30-40 years ago during El Ninos (Hughes et al. 2018a). Bleaching in 2022 is particularly significant because it was the first time, due to ongoing anthropogenic heating, that mass bleaching occurred during strong La Nina conditions. This latest event (which has not yet been fully analyzed) was the 4th mass bleaching in just 6 years.

37) Shallow-water pH and aragonite saturation states are critically important for calcification and other processes on coral reefs. The global average pH of ocean surface waters has declined over the past 200 years by approximately 0.1 units, from 8.21 to 8.10. According to recent IPCC modelling, an equilibrium atmospheric concentration of CO_2 (pCO_2) of 450 ppm will retain a pH of 7.9 to 8.1 in most tropical oceanic waters, which would be sufficient to maintain strongly supersaturated aragonite state throughout the tropics and sub-tropics. To date, there is no evidence that the geographic range of calcifying species is contracting towards the equator due to increasing ocean acidification. (On the contrary, many species are expanding north and south into the subtropics as temperatures rise, despite small decreases in aragonite concentrations).

38) Current atmospheric concentration of CO_2 would have to almost double to 800ppm to reduce the average aragonite saturation state of tropical surface waters by one full unit from its current level of 3.01 to 2.01 Ω_{arg}. Ocean acidification is a much more pressing issue nearer to the poles, where saturation states are close to 1. An atmospheric concentration of 800ppm CO_2 equivalent would have a 50% probability of raising global average temperatures by 5°C (Hughes et al. 2017b). Consequently, global heating is a much more pressing issue for coral reefs compared to the longer-term impacts of ocean acidification. The available experimental evidence suggests that an average decrease in calcification of less than 10% is likely to occur with a more realistic increase in atmospheric CO_2 of up to 500-550 ppm (Hughes et al. 2017b), which corresponds to 2-3°C of global average warming. While a modest level of oceanic acidification will undoubtedly have discernible effects even in the tropics, mass bleaching due to global warming, as well as pollution and overfishing are likely to remain the most pressing challenges for reef biodiversity over the rest of the century.

39) Attempts to restore diminished coral cover through coral gardening, assisted migration (by harvesting larvae) and assisted evolution (rearing corals in an aquarium) are prohibitively expensive and unworkable at any meaningful scale (Condie et al. 2021) (see also paragraph 138). Consequently, the only lasting solution for sustainable protection of corals in Torres Strait and elsewhere is a rapid reduction in global emissions of greenhouse gasses.

(c) *Marine species, including by reference to the risk (if any) of particular species becoming endangered, more critically endangered and/or extinct.*

40) Extinction of species in the marine realm is less common than on land. There are fewer physical barriers to a species' geographic range in the sea – therefore small-scale endemicity is comparatively rare (and population sizes of many marine species are very large). Most of the marine species that have gone extinct in the past century or so are marine mammals, or flightless birds that were endemic to islands. The 2019 Great Barrier Reef Outlook Report provides a list of 18 species in the Marine Park that are listed as Threatened Species under the Environment Protection & Biodiversity Conservation (EPBC) Act 1999 (Cth): One species of mangrove, *Bruguiera hainesii*, 7 species of sharks and rays, all 6 species of marine turtles occurring on the Great Barrier Reef, and 4 species of whales and dolphins. Of these, marine turtles face the high extinction risk from climate change in both the Marine Park and Torres Strait because of their vulnerability of their nests to flooding by rising sea level, and the impacts of higher temperatures on the gender ratio of hatchlings. There is no Listing Advice or Recovery Plan for the dugong in Australian waters under the EPBC Act (because it remains abundant in Torres Strait and westwards to northern Western Australia) despite its long-term decline in abundance throughout most of the Great Barrier Reef World Heritage Area. (For further discussion of extinction risk in Torres Strait, see paragraphs 80-88).

41) The first recorded extinction in Australia of a mammal species due to climate change, was declared by IUCN in 2015: *Melomys rubicola*, endemic to Bramble Cay (Maizab Kaur) in northern Torres Strait. In the decade preceding its extinction, > 90% of the vegetation of the cay was destroyed by sea water inundation due to storm surges and rising sea level. Bramble Cay, similar to many other cays in Torres Strait, has a maximum elevation of just 1m above current sea level. *Melomys rubicola* was particularly vulnerable to extinction because (a) its exposure to sea level rise, (b) its tiny geographic range, with limited food supply and no possibility of being rescued by migrants from elsewhere, and (c) its small population size on one island. The extinction of *Melomys rubicola* in Torres Strait was not recorded in the 2019 Outlook Report because it occurred outside of the Great Barrier Reef Marine Park.

42) Knowledge of a species' abundance throughout its geographic range is critically important for assessing its risk of extinction, but for the vast majority of wild animal and plant species such data are scarce at biogeographic scales. The abundance of corals and sea grasses is typically measured crudely as the percent coverage of the sea floor, pooled for all species. Percent cover has declined (and partially recovered in some cases) for many decades due to climate change and a broad range of other anthropogenic stressors. The rate and scale of this net decline is accelerating as the spatial extent and frequency of mass mortality events increases due to global warming. While some regional trends in overall cover are relatively well understood, we currently know little about the numerical abundance of individual species of coral, seagrass or mangrove species at biogeographic scales (Dietzel et al. 2021b).

43) By definition, global extinction occurs when the last individual of a species dies. Local extinction, where the last individual disappears more locally or regionally (but the species survives elsewhere), is much more prevalent and a step towards global extinction - as the geographic range of critically endangered species shrinks. For example, the dugong is still abundant in Torres Strait (TSRA 2015; TSRA 2021), but comparatively rare in the lower two-thirds of the Great Barrier Reef compared to Torres Strait or to historical abundances, and it is locally extinct in most of its former geographic range in south-east Asia and the tropical Indian Ocean. “Ecological extinction” refers to species that are not yet globally extinct, but which are too rare to perform their historical ecological roles. For example, green turtles and manatees are rare throughout most of their historical geographic range in the Caribbean, leading to under-grazing of seagrass beds in many regions, which has been linked to higher incidences of seagrass disease.

44) Climate change and coral bleaching, and in the longer-term ocean acidification, are the primary reasons for escalating risks of extinction in corals (Dietzel et al. 2021b). Recent assessments of the global extinction risk of coral species have relied on expert opinion and on regional trends in overall coral cover rather than data on the abundance of individual species. Currently, one third of the world’s reef-building coral species are listed by IUCN as either vulnerable to extinction (VU), endangered (EN) or critically endangered (CR).

(d) *Biodiversity in flora and/or fauna, as distinct from the impact to any particular species*

(e) *Marine ecosystems, including reference to processes such as spread of disease and the incidence of pathogens*

45) I have combined my response to (d) and (e) because the effects of Climate Impacts (the four elements of anthropogenic climate change) on overall biodiversity depends on the responses of both species and ecosystems. In scientific usage, the two terms "biodiversity" and "ecosystems" both refer to large groupings of individual species that live together. The incidence of severe diseases in marine species is increasing, and has been linked (e.g. in turtles, corals and seagrasses) to physiological stress due to coastal pollution and rising temperatures. The broader ecological impacts of marine diseases on ecosystems and overall biodiversity are poorly understood. One notable exception is the geographical-scale spread of an introduced pathogen (from the Pacific to the Atlantic via the Panama canal) of the Caribbean sea urchin, *Diadema antillarum* in 1983 (Hughes 1994). The disease outbreak killed 99% of *Diadema* throughout its geographic range, and this formerly-abundant species remains comparatively rare four decades later. Prior to the disease outbreak, *Diadema* was the most important herbivore on most Caribbean reefs, where herbivorous fishes were depleted due to over-fishing. Afterwards, unprecedented blooms of fleshy seaweed occurred, smothering established corals and preventing new larval recruitment. This case study is one of the best documented examples of an enduring regime-shift from dominance by corals to a preponderance of macroalgae (Hughes 1994).

46) Coral reefs and other tropical marine environments support immense biodiversity and provide key ecosystem services to many millions of people. Yet reefs, mangrove and seagrass habitats worldwide are rapidly degrading in response to multiple anthropogenic drivers. Over the coming centuries they will run the gauntlet of climate change, when rising temperatures will transform them into new configurations unlike anything previously experienced by humankind. Returning them to past configurations is no longer an option. Instead, the global challenge is to steer ecosystems through the Anthropocene in a way that maintains biological functions. Navigating this transition successfully will require radical changes in science, management, and governance.

47) It is now widely recognised that biodiversity is more than counts of species, but also includes genetic, phylogenetic, and functional diversity. The morphological, demographic, and life history traits of species play a central role in defining ecosystem functioning. However, critical knowledge gaps remain, in particular, how ecosystem functions will respond to changing species compositions due to climate change and other anthropogenic drivers (see also paragraphs 79-81, 120 and Figures 13 and 20).

48) A defining feature of the emerging Anthropocene Era is the escalation of multiple pressures, such as rapid climate change, globalization and migration, and their effects on society and the world's ecosystems. For example, many coastal coral reefs have been degraded by centuries of overfishing and pollution, and anthropogenic climate change is adding further stress, even on more remote reefs where local pressures are small or absent (GBR Outlook Report 2019). Increasingly, coral reef scientists and managers are confronted with new, previously-unseen configurations of species and diminished biodiversity. The challenge is to identify and maintain the critical ecosystem functions

required to sustain coral reefs, and to secure the future ecosystem services that highly-altered future assemblages can provide to the people who depend on them. Central to this endeavour is an improved understanding of ecosystem function and of the types of management and governance that are effective.

49) Coral reefs are vulnerable to the loss of functionally important species, despite their exceptionally high biodiversity. For example, coral reefs support over 6000 fish species, yet critical functions are often delivered by just a handful of species. A global analysis based on unique trait combinations of fishes revealed that approximately one third of functional groups are comprised of just one species (Mouillot, et al. 2014). The proportion of functional groups of reef fishes that are depauperate (represented by one or two species) is consistent regardless of regional species richness (the total number of species), suggesting that high diversity coral reef hotspots like Torres Strait are just as vulnerable as isolated, low-diversity reefs. Consequently, it is becoming increasingly clear that biodiversity *per se* is less important than the functional composition of reefs – for example for the provision of 3-dimensional habitat (by branching corals), for control of macroalgae (by herbivores), and for the breakdown of dead corals (by bioeroders) to create space for new corals. In the aftermath of recurrent mass bleaching, a seascape dominated by dead, standing corals provides a sub-optimal array of substrates for recolonization by coral larvae. Grazers and bioeroders, such as numerous species of parrot fishes and sea urchins, provide a critical functional role in reconditioning the substrate and promoting coral replenishment.

50) Identifying and targeting the functions that are required to maintain reef ecosystems offers an opportunity for a new approach to both reef management and restoration (Hughes et al. 2017b). For example, herbivorous fishes are functionally important, because their grazing controls the abundance of algae that competes with coral for space. Therefore, as corals continue to decline due to global heating and other stressors, it is important to maintain stocks of herbivores through targeted management. Similarly, the biodiversity of seagrass beds in Torres Strait and elsewhere, is promoted by the feeding trails of dugong, allowing colonization by fast-growing seagrass species that can co-exist with more mature species. Therefore, protecting dugong also has much broader implications for maintaining seagrass habitats.

(f) ***any other aspect of marine life that you consider has a relevant relationship with the Climate Impacts. Together, e-f comprise "Marine Life Impacts".***

51) The capacity of habitat-forming species (corals, seagrasses, mangroves) to persist, reproduce and disperse will be critical drivers of the unfolding trajectory of tropical ecosystems. This important aspect of marine life is not addressed in questions 2a-e, above. In marine systems, the production of larvae and seeds and recruitment of functionally important species are fundamental processes for re-building depleted adult populations, maintaining resilience to anthropogenic climate change, and avoiding ecological collapse in the face of rising environmental pressures.

52) As a consequence of mass mortality of adult coral brood-stock on the Great Barrier Reef in 2016 and 2017 due to unprecedented heat stress, the amount of larval replenishment subsequently declined in 2018 by 89% compared to historical levels (Figure 7). For the first time, brooding corals (primarily *Pocillopora*) replaced spawning species (dominated by *Acropora*) as the dominant taxon in the depleted recruitment pool (Figure 7). This shift is functionally important because it determines the strength and scale of interconnections among individual reefs: Brooding corals are self-seeding at the scale of individual reefs, and typically settle within a day of release. In contrast, spawning corals begin to settle 4-7 days after fertilization, and are more widely dispersed. At the scale of the entire Great Barrier Reef, overall recruitment of corals (brooders plus spawners) after bleaching was reduced to 11.3% of the average levels measured repeatedly over the preceding decades (in 1996, 1997, 1998, 2004, 2015 and 2016).

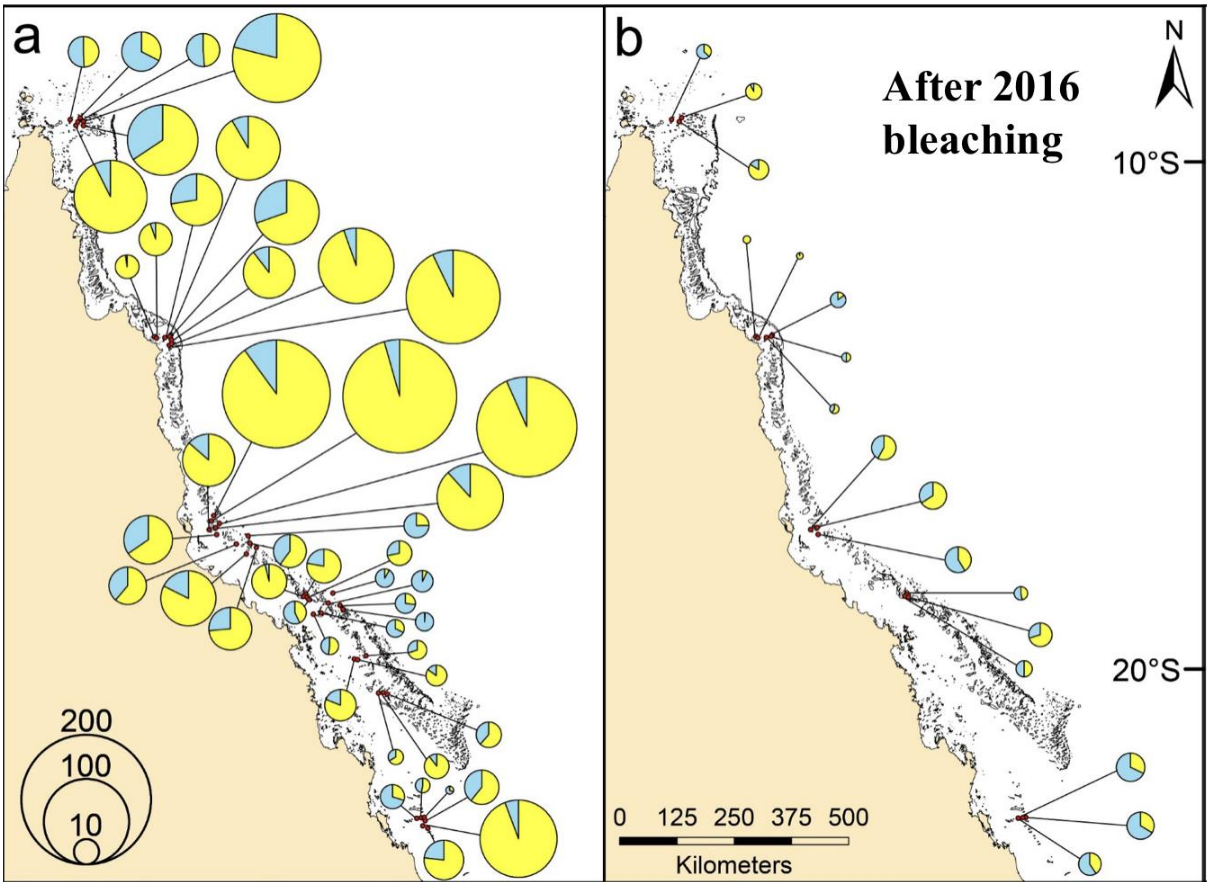

Figure 7. The collapse of coral recruitment along the length of the Great Barrier Reef. A (left): Density of coral recruits, measured repeatedly over three decades, from 1996-2016 (n = 47 reefs, 6 in Torres Strait). B (right): Density of recruits in 2018 after mass mortality of corals in 2016 and 2017 due to back-to-back bleaching (n = 17 reefs, 3 in Torres Strait). The radius of each circle is scaled to show the overall recruit density of spawners and brooders combined. Yellow and blue indicate the proportion of spawners and brooders, respectively (Hughes et al. 2019).

53) The critical processes of replacement of dead corals and population replenishment (by larval recruitment and subsequent colony growth) following a mass bleaching event takes at least a decade to unfold for fast-growing “weedy” corals, such as species of *Acropora, Pocillopora, Seriatopora* and *Stylophora*. Ironically, these species are also among the most susceptible to another peak in temperature, which will increase the impact of subsequent spikes in temperature on recovering reefs if these heat-sensitive species become dominant. A similar dynamic occurs on land – the rapid recovery of flammable grasses following fires caused by drought and higher temperatures, which makes a terrestrial landscape more vulnerable to subsequent fires.

54) The success of coral recruitment depends upon an adequate supply of larvae from lightly bleached or unbleached reefs, the rapid break down of millions of dead coral skeletons to provide a more enduring and stable substrate for settling larvae, and the extent of major disturbances during the recovery period. The gap between one mass coral bleaching event and the next is shrinking worldwide due to rising temperatures. For longer-lived, slow-

growing species, the trajectory of recovery on heavily damaged reefs is far more protracted, almost certainly decades longer than the return-times of future recurrent bleaching events.

55) Similarly, the capacity of seagrasses and mangroves to persist, reproduce and disperse will be critical for their capacity to resist and recover from climate change impacts. Following a climate-related disturbance, such as a flood or heatwave, high connectivity (dispersal of seagrass fragments and seeds), re-growth in surviving plants, and a viable seedbank are key elements to recovery of seagrass populations.

56) The window is shrinking for adequate recovery between one climate-related disturbance and the next (e.g. recurrent coral bleaching events caused by unprecedented heatwaves, die-offs of seagrass due to floods, or the impacts of repeated severe droughts on mangroves). For example, throughout the tropics, the median return-time between pairs of severe bleaching events has diminished steadily since the 1980s, and is now less than six years (Hughes et al. 2018a) – a gap that is far too short for a full recovery, especially of slow-growing and long-lived species. As anthropogenic heating has progressed, tropical sea surface temperatures are warmer now during La Niña conditions than they used to be in El Niño events three decades ago. Consequently, as we transition to the Anthropocene, coral bleaching is occurring more frequently in all El Niño Southern Oscillation (ENSO) phases, increasing the likelihood of annual bleaching in coming decades. Coral bleaching on Torres Strait occurred for the first time during La Nina conditions in 2022, and the first back-to-back coral bleaching events in two consecutive summers occurred in Torres Strait in 2016 and 2017. It is no longer possible for a full re-assembly of the corals reef ecosystems that are repeatedly severely damaged in Torres Strait by anthropogenic heating.

3. *In addressing the relationship between Climate Impacts and the Marine Life Impacts please also:*

(a) ***Identify and explain the extent (if any) to which Marine Life Impacts may have a corresponding effect on the Climate Impacts (for example by way of reinforcing feedbacks);***

(b) ***explain whether the relationship is linear or non-linear; and the concept of tipping points:***

57) I have addressed (a) and (b) together because they are difficult to separate. Arguably, our current thinking about the responses of ecosystems to one or more drivers (e.g. climate change, pollution, over-fishing, etc.) is too linear. The ecological response to one or more stressors is often curved - due to positive or reinforcing feedbacks, e.g. small levels of drivers have no impact (e.g. if pollution is too dilute, or heat stress falls below a threshold) but higher amounts increasingly cause an escalating ecological response (Figure 8). This matters because a non-linear response is harder to predict and manage, and strong feedbacks can produce dangerous threshold (or tipping point) behaviour. Many vulnerable ecosystems, and the people who depend on them, may already have crossed unrecognized tipping points, and are slowly transitioning to new ecological configurations. The switch from a historic ecosystem (e.g. a healthy coral reef) to a degraded one (mostly dead corals with seaweed) is known as a "regime-shift".

58) Changes in marine life due to climate change (Marine Life Impacts) can affect the local environment by storing or releasing carbon. Marine plants can also ameliorate ocean acidification, but also only at a local scale, and only if they survive the impacts of global warming and more local stressors. Carbonate dissolution from the sea floor has not buffered the Great Barrier Reef from decline in pH or in the saturation state of aragonite recorded in recent decades. In general, these marine feedbacks are comparatively small compared to the better-known impacts of terrestrial vegetation on climate (e.g. the reduction in rainfall and increase in fires in the Amazon Basin, which is reinforcing shifts in climate).

59) Blue Carbon has often been proposed as a nature-based solution to climate change, because mangroves and sea grass beds store carbon that would otherwise be released. However, these shallow marine environments only sequester small amounts of carbon each year, and their role in the global carbon cycle is insignificant compared to vastly larger areas of terrestrial vegetation. Importantly, sea grasses and mangroves release very large amounts of greenhouse gasses when they experience mass die-offs, including substantial losses due to anthropogenic heating. Thirty-six percent of the sea grass beds in Shark Bay, Western Australia, were killed over an area of 1,100km^2 by a marine heatwave in 2010/2011 (Arias-Ortiz et al., 2018). The die-off was initiated when Sea Surface Temperatures rose by 2˚C-4˚C above the long-term average summer maximum, lasting for more than two months. Afterwards, water clarity decreased due to loss of sediments, and widespread blooms of phytoplankton and bacteria were triggered by released nutrients. This example of a seagrass die-off released an estimated 2–9 million tonnes of CO_2 (Arias-Orrtiz et al. 2018).

Similarly, in 2016, the unique mass mortality of 40 million mangrove trees across more than 2,000 kilometres of coastline in the Gulf of Carpentaria released nearly 1 million tonnes of carbon (Duke et al. 2022).

60) Ecosystems can respond in fundamentally different ways to gradual increases in chronic, slow acting drivers such as rising greenhouse gas concentrations, global warming and ocean acidification. The ecological response may be incremental or "smooth" as drivers increase, and reversible along the same trajectory if the drivers decrease (Figure 8a). Alternatively, there may be a threshold in the response, which is also easily reversible if the driver(s) are reduced (Figure 8b). Or thirdly, strong feedbacks can cause the response curve to fold, causing the system to exhibit "hysteresis" (Figure 8c). Hysteresis makes recovery very difficult, because the threshold level of driver for recovery occurs at a lower level than the threshold for collapse. Two thresholds are shown in in Figure 8c, indicating that drivers would need to be reduced to a lower level to allow recovery (on the left) compared to a higher threshold of drivers that triggers collapse (on the right). For an intermediate range of drivers, between the lower and upper thresholds, two alternative stable states are possible (e.g. a healthy or degraded coral reef). The reversibility of regime-shifts and the prevalence of hysteresis and alternate stable states are poorly understood, in part because most ecological systems are under sustained human pressure, and there have been few experimental attempts to reduce levels of drivers (from right to left in Figure 8) at large scales. Regime-shifts can be sudden ecological surprises, or the transitions between ecological regimes may unfold slowly, with major consequences for our capacity to detect, avoid or reverse them.

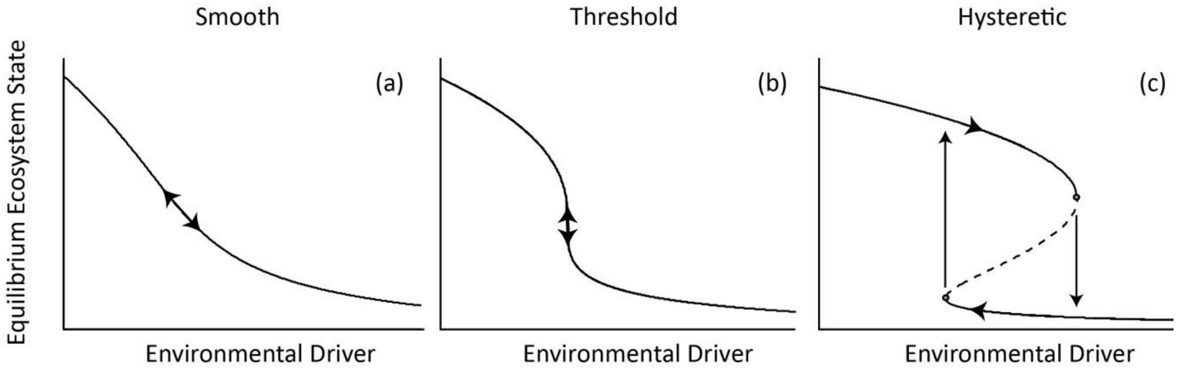

Figure 8. The response of a dynamic system (at equilibrium) to slowly changing conditions or drivers can be (a) smooth, (b) a pronounced change at particular conditions, or (c) a transition between two alternate regimes, showing hysteresis. (Hughes et al. 2013).

61) Thirty different positive feedbacks have already been documented on coral reefs (Van de Leemput et al. 2016). Some of these observed feedbacks are ecological, some are social, and others are both. For example, when fish stocks decline, fishers without access to an alternative livelihood often increase their fishing effort and further suppress the stocks. A strong feedback produces a threshold response (Figure 8b), and a stronger one still can cause hysteresis (Figure 8c) and precipitate a catastrophic collapse. When multiple weak

feedbacks act simultaneously, they can collectively promote an unexpected regime-shift as multiple drivers gradually increase.

62) Multiple elements of anthropogenic climate (“Climate Impacts”) are now the most pervasive chronic drivers of ecological change. The Arctic sea-ice and its associated ecosystems and species is one system that exhibits threshold dynamics, where a switch to a new equilibrium is unfolding (Figure 8c). Positive albedo-feedbacks in energy-balance models of this system predict two alternate regimes, either a stable amount of ice and snow cover, or ice-free conditions (initially during summer, but later a year-round shift will occur under future climate change scenarios). Reflective snow and ice encourages one stable alternative, while heat absorption by open water reinforces the other. Arctic ice has been melting much more quickly than IPCC projections, due to rapidly rising temperatures and associated changes in currents.

63) The responses of coral assemblages to heat exposure, measured in Degree Heating Weeks, is another example of a non-linear relationship (Figure 9). Responses by coral assemblages on the Great Barrier Reef and Torres Strait were small on reefs that were exposed to DHW <6 ^{o}C-weeks, and most corals survived. In contrast, reefs subjected to >6 ^{o}C-weeks lost more than half of their corals, and the mix of species shifted dramatically (Figure 7).

64) Satellite-derived data from NOAA with 5km resolution indicated that 28.6% of the 3,863 reefs comprising the Great Barrier Reef and Torres Strait experienced thermal exposures of >6 ^{o}C-weeks during the 2016 bleaching event, and 20.7% (800 reefs) were exposed to >8 ^{o}C-weeks (Hughes et al. 2018). Individual reefs with this severity of heat exposure have undergone an unprecedented collapse, extending southwards from Papua New Guinea for up to 1,000 km (Figure 5). Reefs that escaped moderate or heavy bleaching in 2016 were located in the southern half of the Great Barrier Reef, and in a small norther-eastern patch in Torres Strait at the outer edge of the continental shelf where temperature anomalies in 2016 were small.

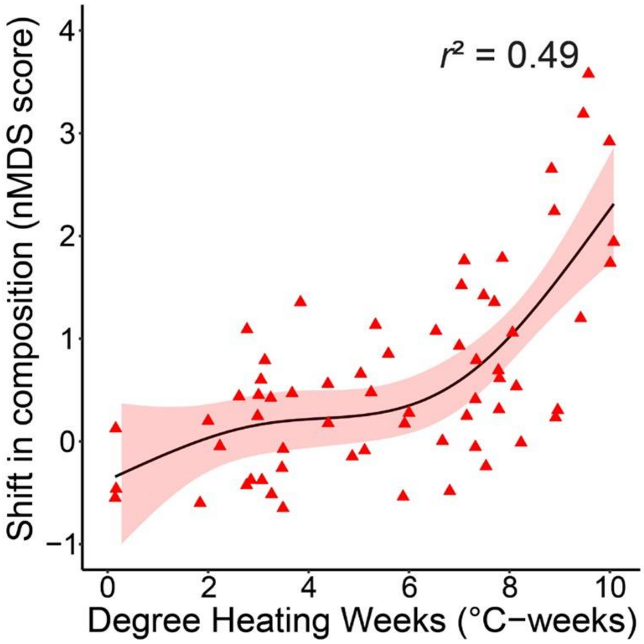

Figure 9. Change in coral assemblages on the Great Barrier Reef and Torres Strait in response to heat exposure, illustrating a non-linear response. Regression curve is fitted using a Generalised Additive Model (GAM), with 95% confidence limits. Each data point represents the shift in composition, based on the Euclidean distance in a non-metric multi-dimensional scaling analysis of assemblages on individual reefs sampled at the peak of bleaching in 2016 and eight months later. Heat exposure for each reef is measured as satellite-derived Degree Heating Weeks (DHW, °C-weeks).

65) Models that explicitly include feedbacks and non-linear interactions within ecological systems are useful for understanding and analyzing their dynamics. For example, the role of multiple drivers and feedbacks is is explored in Figure 10. When three drivers (climate change, overfishing and pollution) are modelled simultaneously, their interactive effects become more evident, resulting first in transitions from a coral state to alternate states, (where coral and non-coral states can both occur), and ultimately to conditions where only the macroalgal state is possible. Consequently, the model identifies the concept of a generic safe operating space for coral reefs - where corals can remain dominant so long as multiple drivers are held in check below threshold levels arising from their combined impacts.

66) This modelling result is particularly germane for the widespread emergence of new drivers affecting ecosystems that add to the impact of pre-existing stressors (which themselves are likely to be strengthening over time). For example, climate change and new coastal developments are adding to the ongoing century-old pressures of overfishing and pollution on marine ecosystems. The modelling supports the empirical observation that climate change is a threat even on the most remote and pristine reefs, where pollution and overfishing is minimal, and that local action to protect reefs from overfishing and pollution can only increase the resilience of coral reef ecosystems when climate change pressures are low. Furthermore, the modelled result (Figure 10) indicates that synergistic human

impacts can reduce resilience and cause unexpected ecological collapse, even when individual drivers or stressors remain at relatively low levels that are safe. The challenge for the future is to steer away from regional-scale tipping points that are already manifesting at local scales.

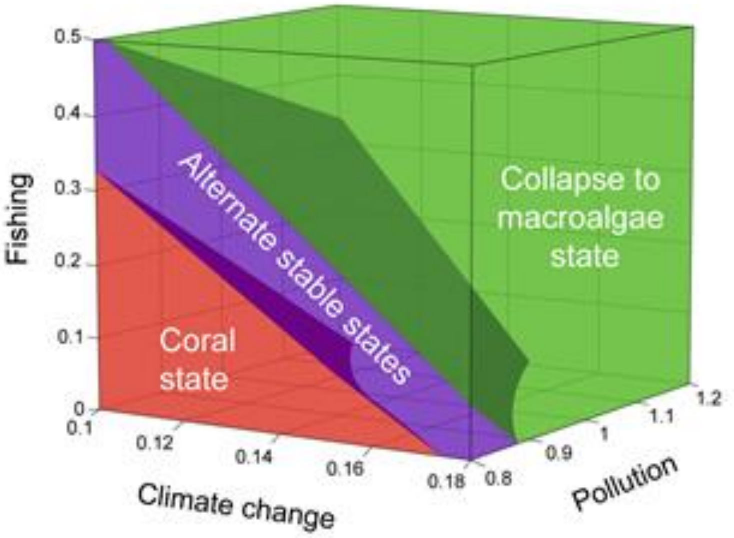

Figure 10. The modelled response of coral reefs to three drivers: climate change, pollution and fishing. Depending on the strength and interaction between the drivers, three outcomes are possible: healthy coral-dominated assemblages (red) when drivers are weak, macro-algae with few corals (green) when drivers are strong, or an intermediate condition where alternate stable states can occur (purple). The interface between the coral, alternate and macro-algal states represent the tipping points or thresholds for each combination of drivers. The coral state collapses if stress from any one driver is too strong, and is eliminated entirely by the cumulative impacts of multiple drivers. The width and shape of the purple region with alternate stable states depends on the strength of interacting feedbacks (Hughes et al. 2017b).

(c) ***explain whether there is any variation geographically (that is, whether the relevant Climate Impacts affects the relative Marine Life Impact in the same way and to the same extent everywhere around the world).***

67) Climate change elements all vary spatially at local, regional and geographical scales. The IPCC reports, for example, provide global maps illustrating contours and gradients of recent and projected temperatures, precipitation, ocean pH, etc. Similarly, global maps can also show the spatial patterns in the responses of key species and ecosystems to climate change, such as the incidence and severity of coral bleaching, or the distribution of species threatened with extinction. Here, I provide examples of geographic variation in ocean temperatures, coral bleaching, and sea level rise – and discuss their implications for documenting the condition of the Great Barrier Reef and Torres Strait. Geographic variation in Marine Life Impacts in Torres Strait are discussed in Question 5.

68) The observed increases in annual Sea Surface Temperatures in the tropics and sub-tropics since the late 19th century has varied substantially at regional and local scales, with 71% of reefs worldwide warming so far by 0.25-0.75ºC (Figure 11). This spatial heterogeneity suggests that there is no single safe level of global emissions for all coral reefs, because some are warming faster than others. For example, Torres Strait waters have warmed so far less than the southern Great Barrier Reef. Future temperature increases will also vary greatly in space and time, highlighting the need for improved regional-scale measurements and modelling.

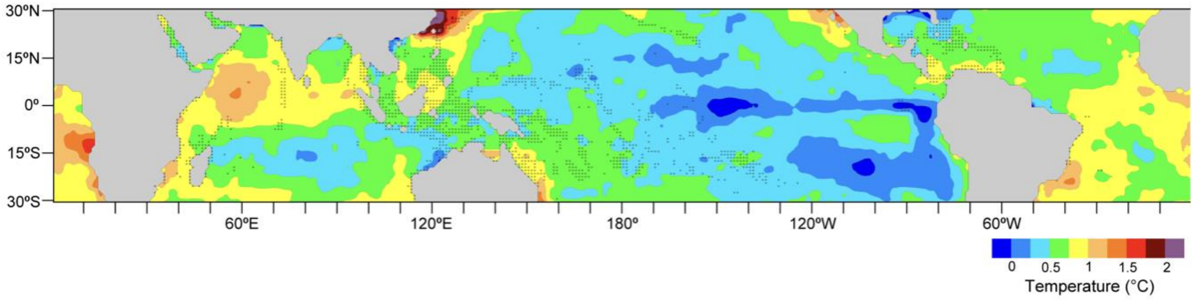

Figure 11. Global trends in tropical sea surface temperature (SST) over the period 1880-2015. Rates of warming of annual average SST were calculated for all 1-degree latitude by longitude boxes between 30.5ºN and 30.5ºS (Hughes et al. 2017b).

69) Future Sea Surface Temperatures under the IPCC's RCP2.6 scenario are projected to increase in the short-term (for 2010-2039) in all major coral reef provinces, even as global emissions peak and begin to fall. Further warming projections for this period range from +0.48ºC in the Caribbean region to +0.32ºC in the eastern Indian Ocean. From 2039-2099, as temperatures begin to stabilize, SSTs are projected to change further by +0.20ºC to -0.05ºC across reef provinces. Consequently, the longer term warming trend up to the end of this century, under this low emissions scenario, varies among reef provinces from +0.30 to +0.68ºC, an additional amount that is roughly equivalent to the warming so far over the past century. Higher emissions than the RCP2.6 scenario could generate much more warming (IPCC 2018). Even if the Paris Agreement comes close to the 2ºC target, this

projected level of warming will have very severe consequences for coral reefs, particularly when temperatures spike above long-term summer maxima, leading to recurrent bleaching events.

70) A recent global analysis also reveals strong geographic patterns in the timing, severity and return-times of mass coral bleaching (Figure 12). The Western Atlantic, which has warmed earlier than elsewhere, began to experience regular bleaching early, with an average of 4.1 events per location prior to 1998, compared with 0.4 to 1.6 in other regions. Furthermore, widespread bleaching (affecting >50% of locations) has now occurred seven times since 1980 in the Western Atlantic, compared to three times for both Australasia and the Indian Ocean, and only twice in the Pacific. Over the period 1980-2016, the number of bleaching events has been highest in the Western Atlantic, with an average of 10 events per location, 2-3 times more than other regions (Figure 12).

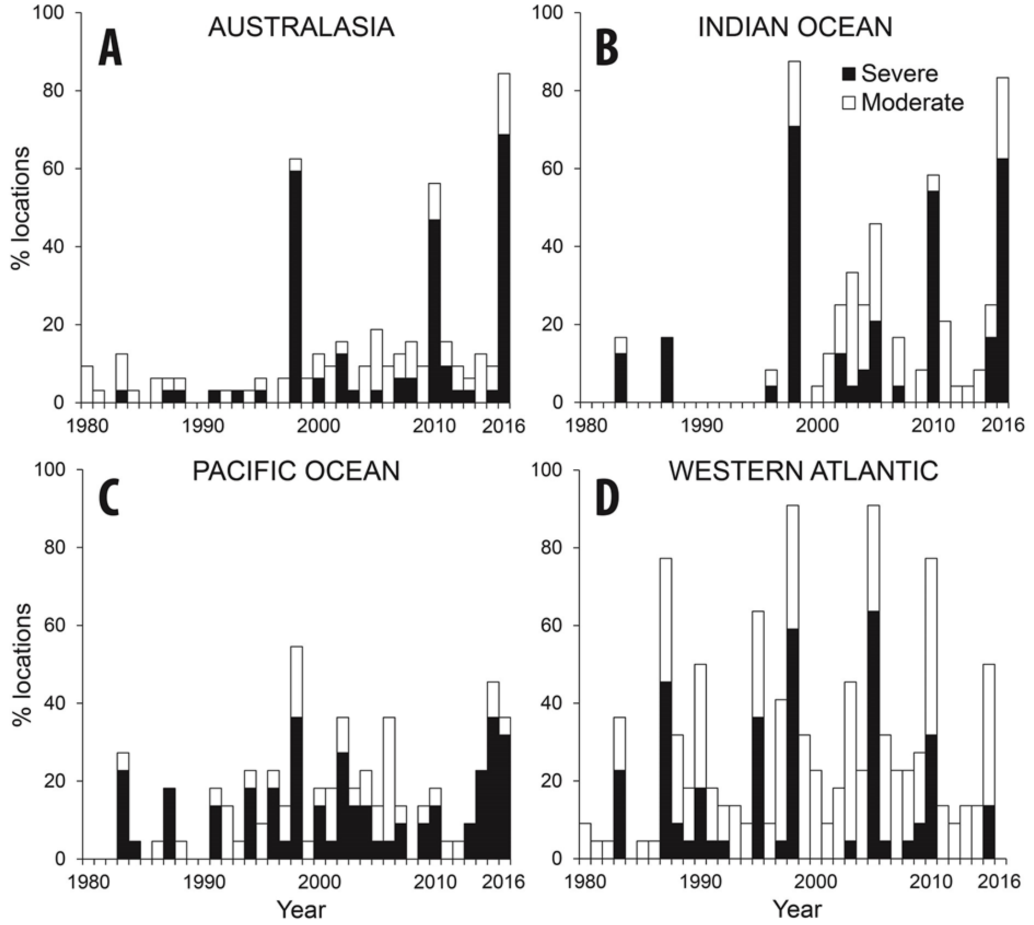

Figure 12. Geographic variation in the timing and intensity of coral bleaching, from 1980-2016. (A) Australasia (32 locations). (B) Indian Ocean (24 locations). (C) Pacific Ocean (22 locations). (D) The Western Atlantic (22 locations). For each region, black bars indicate the percentage of locations that experienced severe bleaching, affecting >30% of

corals. White bars indicate the percentage of locations per region with additional moderate bleaching affecting <30% of corals (Hughes et al. 2018(a)).

71) In the 1980s, bleaching risk was highest in the Western Atlantic, followed by the Pacific, with the Indian Ocean and Australasia having the lowest bleaching risk. However, bleaching risk has increased most strongly over time in Australasia and the Middle East, at an intermediate rate in the Pacific, and slowly in the Western Atlantic (Figure 12).

72) Sea level rise is also spatially variable at global, regional and local scales (White et al. 2015). For example, sea level is rising faster in Australia's northern areas. On the Great Barrier Reef, the average rate of sea level rise in 1993-2018 was 5-7mm per year, and more locally up to 12 millimetres per year (GBR Outlook Report 2019), well above the global average of 3-4mm. Sea-level rise directly threatens low lying islands and coastlines. The height of extreme sea-level events (e.g. due to king tides and storm surges) will increase as average sea level continues to rise, causing severe damage to [redacted] coastal habitats. The inevitable equilibrial sea level rise due to 1.5°C or 2°C of global average warming is sufficient to eventually drown low-lying islands and coastlines throughout the world.

73) Assessments of the condition of the Great Barrier Reef in the Commonwealth's Great Barrier Reef Outlook Reports (in 2009, 2014 and 2019) and in Australia's annual State Party Reports to UNESCO are overwhelmingly presented at the scale of the entire Great Barrier Reef region (excluding Torres Strait). However, more local-scale data are critical for understanding and documenting the trajectory of different elements of the Great Barrier Reef. For example, mangroves, seagrasses and reef habitats have distinctive patterns of distribution across Torres Strait, and many processes such as coral growth, outbreaks of crown-of-thorns starfish and larval recruitment by fishes and corals show distinct north-south latitudinal gradients. Similarly, coral bleaching (in 1998, 2002, 2016, 2017, 2020 and 2022), and subsequent mortality and recruitment of corals, all show complex multi-scale spatial patterns that have already affected the condition and Integrity of the Great Barrier Reef World Heritage Area, both locally and region-wide (Question 7).

74) The Great Barrier Reef (including Torres Strait) has already become more patchy and more fragmented, with highly altered patterns of connectivity between areas with different recent histories of climate-related disturbance (Hughes et al. 2018b). Australia's 2014 State Party Report to UNESCO noted briefly that the condition of the Great Barrier Reef was increasingly patchy: "*While activities within the property* (the Great Barrier Reef World Heritage Area) *are comprehensively managed and use is generally sustainable, the remoteness of some of the property poses challenges for managing agencies. This, and previous assessments, have demonstrated that the most significant impacts on the property's values arise from external pressures such as climate change, catchment run-off and coastal development. In the southern two-thirds of the Region, where there are greater levels of development, the condition and trend of some values are in decline.*" Two years later, the relatively pristine northern third of the Great Barrier Reef and Torres Strait bore the brunt of the 2016 mass bleaching event (Figure 5).

75) Torres Strait and the Great Barrier Reef more broadly have now become a checker board of individual reefs that have each experienced from zero to four coral bleaching events since 2016. This increased level of heterogeneity will continue to escalate as climate change progresses in coming decades (Figures 5a and 19a).

IV. MARINE LIFE IMPACTS IN TORRES STRAIT

4. Please identify which of the Marine Life Impacts (if any) are of particular significance to marine life in Torres Strait ("Torres Strait Impacts"), including by reference to:

a) relevant species of flora (such as seagrass) and fauna (such as lobsters, green turtles, dugongs); and

b) relevant aspects of biodiversity

76) I have answered Questions 4a and 4b together because significant gaps persist in detailed knowledge of long-term trends in the condition of the vast majority of individual marine species in Torres Strait (see further detail below). In Question 3, "Marine Life Impacts" refers to the Climate Impacts on a) mangroves and coastal wetlands; b) coral bleaching events; c) marine species, including extinction risk; d) biodiversity; e) marine ecosystems, and f) the replenishment capacity of depleted populations. The succinct answer to Question 4 is that *all* of these six elements of Marine Life Impacts are of particular significance to marine life in Torres Strait ("Torres Strait Impacts"). In Question 7, I provide a comprehensive account of the Torres Strait Impacts already arising from the current level of anthropogenic heating (approximately 1.2^{o}C of global average warming, so far). To avoid repetition, I focus here on the vulnerability of Torres Strait's marine biodiversity, ecosystems and iconic species to Climate Impacts and other drivers - why are some Torres Strait species more vulnerable than others? These vulnerabilities depend on specific species traits (e.g. heat tolerance, mobility, life history, diet) and on complex interactions among species - in particular, on the predator-prey (food web) relationships among species, and on the provision of habitat by structural and habitat-forming species such as corals.

77) With some exceptions, most of the available information on the responses of ecosystems and overall biodiversity to Climate Impacts focusses on aggregates of many species, e.g. "corals", mangroves" or "seagrasses". According to the latest State of Environment Report Card: *"There are still large gaps in science knowledge and data in relation to trends in dugong abundance and movements, turtle abundance and movements, whales and dolphins, sharks and rays, non-commercial pelagic fish, littoral zone species, marine molluscs, crocodiles, invertebrates, mangrove crabs,* (and) *fungi…"* (TSRA 2021). For example, the Report Card provides no information on barramundi, prawns, rays or rock lobsters[redacted]. Species-level data in the scientific literature from Torres Strait are generally limited to a small number of comparatively well-known mega-fauna, including dugong, turtles, saltwater crocodile, and to culturally and commercially important fisheries (Butler et al. 2012, Johnson and Welch 2016).

78) Sea-level rise and increased temperatures are already damaging nearshore ecosystems habitats in Torres Strait, such as mangroves, mudflats and beaches, coastal wetlands and sea grasses, and intertidal coral reefs (see Question 7). Future sea-level rise and higher temperatures may also exceed the adaptive capacity of subtidal ecosystems, including seagrasses and coral reefs, especially if they are also stressed by more local anthropogenic

impacts (e.g. coastal pollution, runoff of sediment during flood events). The biodiversity and mix of species (species composition) of all types of marine ecosystems is already changing rapidly due to differences in susceptibility to heat stress among species, and to differences in their capacity to rebound between recurrent temperature extremes and other climate-related disturbances. Nesting marine turtles and birds are particularly vulnerable to loss of rookeries from sea level rise, and to the impacts of rising temperatures on the gender ratio of hatchlings (Jensen et al. 2018).

79) The structure and dynamics of food webs (Figure 13) illustrates the dietary inter-dependencies among species, and how the loss of primary producers due to Climate Impacts (corals, algae, seagrasses, mangroves, at the bottom of the food web) can subsequently affect herbivores (sea urchins, parrotfish, dugong, green turtles), and secondary and primary predators (e.g. lobsters, reef fishes, sharks, crocodiles and seabirds, at the top of the food web). These different layers in a food web are referred to as trophic levels, and the interaction between them is known as a trophic cascade. (Two examples of trophic cascades were presented earlier in this report – the impacts on corals and seaweed of the die-off of herbivorous sea urchins due to disease in the Caribbean (Question 2(d)), and the effects on tiger sharks and dugong of mass mortality of seagrasses in Shark Bay, Western Australia due to anthropogenic heating (Question 2(a)).

80) The specialist diet of dugong and green turtles makes them especially vulnerable to loss of sea grasses due to Climate Impacts. In Torres Strait, diebacks of sea grasses have resulted in significant local mortality and loss of physiological condition of dugong (Marsh et al. 2004). Conversely, the biodiversity of seagrass beds in Torres Strait and elsewhere, is promoted by the feeding trails of dugong, allowing colonization by fast-growing seagrass species that can co-exist with more mature species. Therefore, protecting dugong has much broader implications for maintaining seagrass habitats, and visa-versa. Similarly, outbreaks of crown-of-thorns predators in Torres Strait has a detrimental impact on their coral prey, and impeded recovery of coral populations that are depleted by mass bleaching (TSRA 2021).

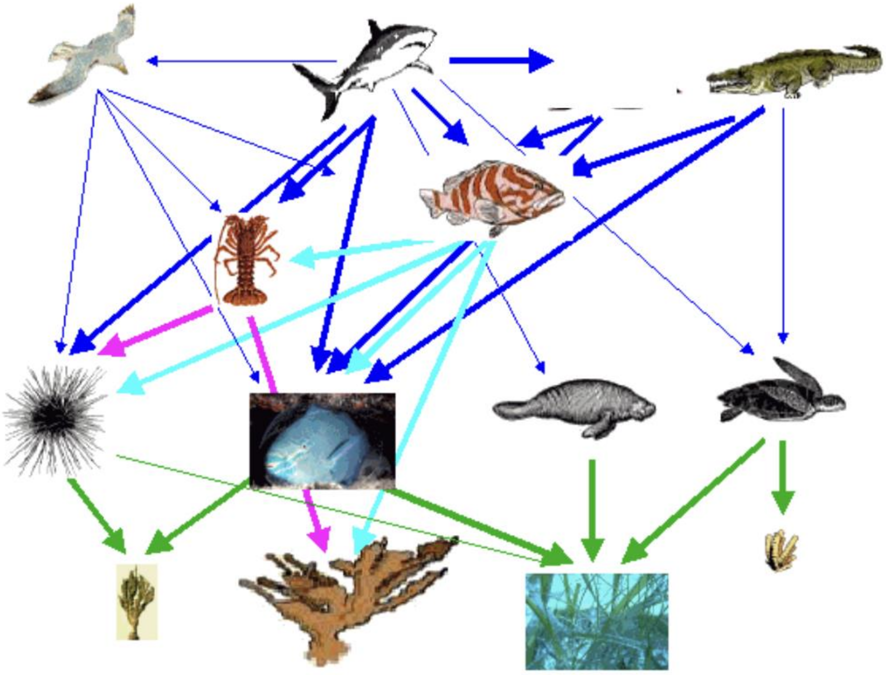

Figure 13. An idealized tropical marine food web. Arrows indicate dietary linkages.

81) In addition to food web linkages, habitat-forming species (mangrove plants, sea grasses, and corals), play a critical role in regulating the abundances of thousands of species that depend on them for shelter and protection. Loss of habitat is a key driver of declines in biodiversity, and the reason why monitoring focusses heavily on these key structural species. Monitoring of seagrass beds in Torres Strait, particularly in deep water, and in the north-west and eastern parts of Torres Strait, remains patchy and incomplete (Carter et al., 2022). Similarly, only fragmented information is available for corals, often with long gaps between repeated censuses (TSRA Outlook Report 2022). Sessile species (i.e. species that don't move as adults) are often combined in monitoring reports into higher-level grouping, such as "corals" or "seagrasses", using quite crude metrics such as percent of the substrate covered by many species.

82) Torres Strait's mangroves are highly diverse, encompassing approximately 40 mangrove species, representing roughly half of the world's mangrove species. Seagrass beds (or meadows) in Torres Strait provide habitats that support many species (high biodiversity) including the largest remaining populations of endangered dugongs and green turtles in the world. Seagrass beds and associated species are critical for local fisheries, [redacted]. These habitats are internationally significant because of their large area and exceptionally high species richness in comparison to the rest of the Indo-Pacific (Coles et al. 2003). Recovery following die-backs in seagrass meadows that are dominated by *Halophila* species is generally faster because *Halophila* are comparatively fast-growing, and they produce large amounts of seed that

remain viable in seed banks for at least two years (Carter et al. 2022). However, most seagrass monitoring programs provide little information at the species level.

83) Six of the seven species of marine turtle in the world have been recorded in Torres Strait region. Two of them are recorded only occasionally – the olive ridley turtle (*Lepidochelys olivacea*), and the leatherback turtle (*Demochelys coriacea*). A third, the loggerhead turtle (Caretta caretta) forages in Torres Strait but nests elsewhere. The green (*Chelonia mydas*), hawksbill (*Eretmochelys imbricata*) and flatback (*Natator depressus*) turtles all nest and forage in Torres Strait. The Flatback turtle has the smallest geographical range of these species, and is endemic to tropical Australia and Papua New Guinea. The rest are much more widely spread, but listed as "endangered" under the USA Endangered Species Act in most parts of their geographical range where they are now rare or ecologically extinct. In Australia, the leatherback, loggerhead and olive ridley are listed as endangered under the Commonwealth's EPBC Act, while the green, hawksbill and flatback are listed as vulnerable. The (vulnerable) green turtle – the most numerous species in Torres Strait – is herbivorous, and like the dugong, is highly sensitive to diebacks of sea grass beds due to climate change. Nesting turtles are also highly susceptible to increasing feminization of hatchling due to rising temperatures, and to drowning of nests due to sea level rise and storm surges.

84) Raine Island, in the far north of the Great Barrier Reef Marine Park, is the largest surviving rookery for green turtles in the world. Females congregate there to nest, drawn from a population that forages widely in Torres Strait and elsewhere. According to the 2019 Great Barrier Reef Outlook Report: "*Since the mid-1990s, concerns have been expressed about declines in nesting and hatchling success of green turtles nesting at Raine Island…. Given an estimated 90 per cent of northern population females nest on Raine Island or nearby Moulter Cay, there may be significant implications for the northern population as a whole. Warming temperatures are resulting in the feminisation of green turtles originating from nesting beaches in the northern Region, potentially leading to significant scarcity or absence of adult males in the future.*"

85) On cooler nesting sites in the southern Great Barrier Reef, green turtles already have a moderate female bias - 67.8% of juveniles, 64.5% of sub-adults, and 69.2% of adult individuals are females (Jensen et al. 2018). In contrast, turtles that have hatched on Raine Island and elsewhere on the far northern Great Barrier Reef and in Torres Strait are now extremely female dominated (99.1% of juvenile, 99.8% of subadult, and 86.8% of adults). Due to rising temperatures, the northern green turtle population has been hatching mostly females for more than two decades (Jensen et al. 2018). It is unclear how long the population will breed and survive when males decrease in abundance even further due to rising temperatures.

86) The saltwater crocodile (*Crocodylus porosus*) occurs throughout Torres Strait, from coastal creeks and mangrove habitats in the west, to seagrass and reef systems eastwards across the region. Estimates of population size and movements in and out of the region are sparse. The main threats to crocodiles are poaching, loss of habitat including estuarine nesting sites (Question 2a), and anthropogenic heating. In particular, (similar to nesting turtles) the sex

ratio of crocodile hatchlings is temperature-dependent, with higher temperatures skewing the ratio towards more females (Grigg and Kirshner 2015).

87) The population of the dugong, *Dugong dugong* in Torres Strait is the largest in the world. This iconic species is listed as vulnerable to global extinction on the IUCN Red List of Threatened Species. Its geographic range extends historically to 48 countries, and includes the Red Sea, Gulf of Persia, East Africa and the tropical Indian Ocean, the Coral Triangle region in the central Indo-Pacific and north to southern Japan, northern Australia, and eastwards across the western Pacific to New Caledonia and Vanuatu. Dugong are very rare or ecologically extinct in most of their former range due to hunting, boat strikes, fishing net drownings, and to the global decline in seagrass beds due mainly to coastal pollution, dredging for ports, and anthropogenic climate change.

88) The Bramble Cay melomys, *Melomys rubicola*, was declared extinct by IUCN in 2015. (see Question 2c, paragraph 41), This species of rodent was found only on Bramble Cay (Maizab Kaur) in northern Torres Strait. In the decade preceding its extinction, > 90% of the vegetation of the cay was destroyed by sea water inundation due to storm surges and rising sea level due to anthropogenic climate change.

89) Key species (or species groups) that support fisheries in Torres Strait include tropical rock lobster (TRL), prawns, barramundi, reef-associated and pelagic fishes, sea cucumber, *Trochus* snails, and pearl oyster (Johnson and Welch 2016). Stocks of the last three were severely depleted historically by overfishing, and their numbers remain comparatively very low today (Ganter 1994). Reef-associated fisheries are particularly vulnerable to the loss of corals due to coral bleaching caused by temperature extremes. Higher sea surface temperature, longer wet seasons, rising sea-level and ocean acidification are likely to have further significant impacts on these fisheries (Hobday et al., 2006). The 2019 Great Barrier Reef Outlook report provides limited information on the status of dugongs, turtles and sea cucumbers in Torres Strait. The black teatfish sea cucumber was considered to be one of the most vulnerable Torres Strait fisheries species to climate change impacts due to its limited mobility, exposure to warmer, shallow reef areas, and its low rate of population replenishment (2019 GBR Outlook Report). Many other species in Torres Strait share these traits.

90) According to the Torres Strait Regional Adaptation and Resilience Plan (2016-2020):

> *"Key vulnerabilities* (of fisheries) *include the sensitivity of coral reef systems to temperature and acidification, vulnerability of key fish breeding habitats such as mangrove systems to sea-level rise, and a shift in distribution and abundance of target species to cooler waters. Increased storm intensity and higher storm surge can increase turbidity. Increased wet season rainfall coupled with ongoing land clearing in PNG might also increase runoff into the region, further affecting some aspects of fisheries. Infrastructure that supports fishing, such as jetties and wharves, is at risk from sea-level rise and storm surge* (TSRA 2016)*."*

5. ***In respect of each of the Torres Strait Impacts, please:***

a) ***specify whether that impact is relevant to the whole of the Torres Strait; or***

b) ***identify that part of Torres Strait to which the identified impact is relevant (for example, by reference to a specific island)***

and explain how the identified impact is relevant in that context.

91) In Question 3c, I described large-scale geographic variation (that is, “whether the relevant Climate Impacts affects the relative Marine Life Impact in the same way and to the same extent everywhere around the world”). Here, the focus is specifically on Torres Strait, with respect to the Torres Strait Impacts documented in Question 4. Torres Strait encompasses a broad array of different habitats and ecosystems. This spatial heterogeneity, along with variable gradients in many physical variables (e.g. depth, exposure, salinity, turbidity, currents, etc.) ensures that the impacts of climate change are patchy at multiple spatial scales. Here I consider examples of spatial patterns in the responses of mangroves, coastal wetland, and coral reefs in Torres Strait to climate change, so far, where possible by reference to specific islands. As explained in Question 4, mangrove vegetation, seagrasses and corals provide vital three-dimensional habitat and structure that supports thousands of associated species.

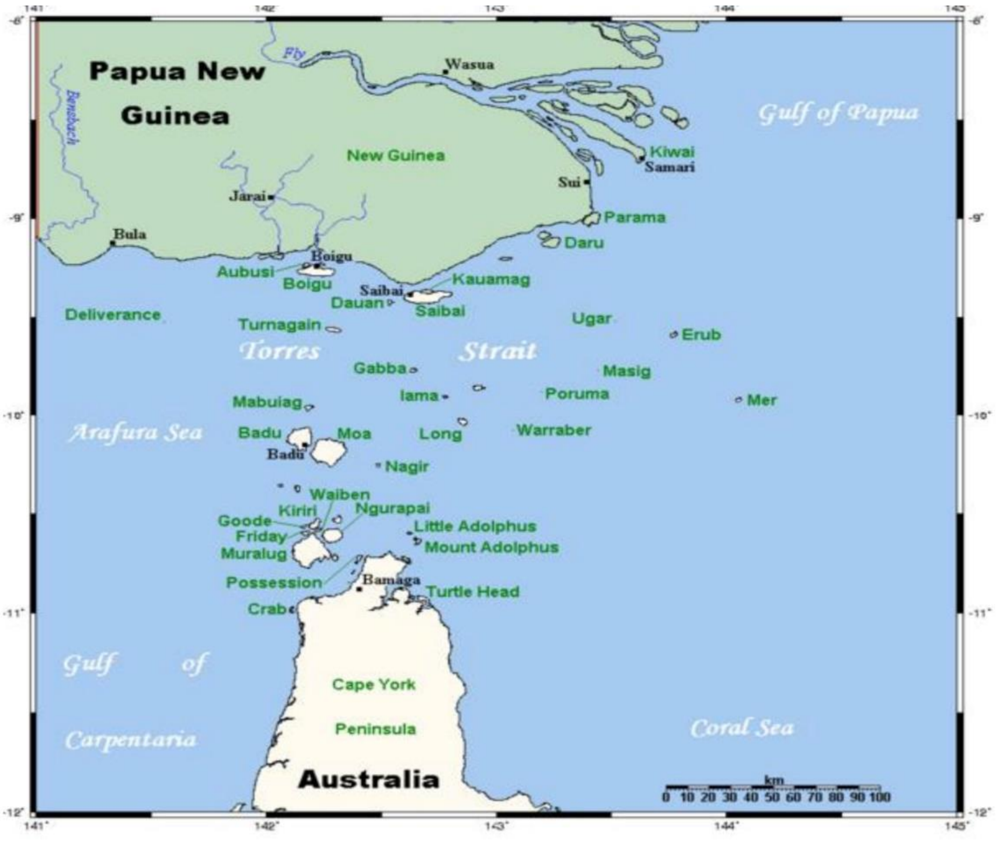

Figure 14. Map of Torres Strait, showing some of the place names in this report. (Welsh and Johnson 2013).

92) Approximately 30,000 ha of tidal wetlands occur widely in Torres Strait - predominantly mangroves, as well as smaller areas of saltmarsh, saltpans and limited amounts of freshwater or brackish wetlands (TSRA 2021). Well-developed mangrove habitats occur on Buru Island (Turnagain) in the northwest and on Sassie and Zagai further east (Figure 15). Persistent freshwater swamps occur only on larger continental Islands - Badu, Moa and Muralug (Prince of Wales Island) in the west. Sea level rise due to climate change, along with storm surges, king tides and ENSO-related tidal anomalies, have already caused significant damage to these habitats, and created new hypersaline wetlands on Boigu and Saibai, near coastal Papua New Guinea (Figure 14).

93) The Fly River in Papua New Guinea is the biggest source of sediment and nutrient runoff in the region, and its flood plumes regularly impact on coastal habitats in northern Torres Strait. To the west, the larger continental islands have much smaller rivers and creeks, principally on Horn Island (Ngurupai), Badu and Moa. [redacted] Saltwater inundation will increase as sea level continues to rise.

94) The condition of a small number of seagrass sites across Torres Strait is regularly monitored by the Torres Strait Seagrass Monitoring Program, which suggest that climate impacts so far on seagrass habitats vary spatially across Torres Strait. The 2020 and 2021 Torres Strait Seagrass Report Cards found significant declines in seagrass condition in the Orman Reefs and Mabuyag Island in the west. The declines were widespread across intertidal and sub-tidal habitats. The 2022 Report Card documents annual to decadal-scale trends in the condition of seagrass habitats at 27 sites in the Western, Central, Eastern and Inner island clusters (Carter et al. 2022). Monitoring is patchy and has not been established in the Top-Western Cluster (Figure 15). Subtidal seagrass biomass at sites in the Western and Central clusters showed no signs of recovery following earlier large-scale declines. The causes of these die-offs are poorly understood because of the infrequency of monitoring.

95) Substantial diebacks of seagrasses have been documented in Torres Strait since the 1970s, resulting in some cases in significant local mortality and loss of physiological condition of dugong (Marsh et al. 2004). An extensive survey of mangroves and wetlands in 2012-2014 concluded that the mangroves and tidal wetlands of Torres Strait were in “moderate” condition. The survey documented “significant indications of longer term, deteriorating trends and widespread damage” due to rapid rises in sea levels as well as local impacts. Between 2018-2021, more recent declines in seagrass condition were observed in western Torres Strait, across both intertidal and subtidal seagrass habitats. Loss of vegetation also increases erosion of sediments and their suspension in the water column. In addition to the impacts of severe weather and sea level rise, the local stressors to mangroves and tidal wetlands of Torres Strait include invasive species (climbing perch, Gambusia, Tilapia, deer, pigs, cane toads, rats, cats, dogs, and invasive weeds), overextraction of groundwater, and damage from tracks and vehicles (TSRA 2021).

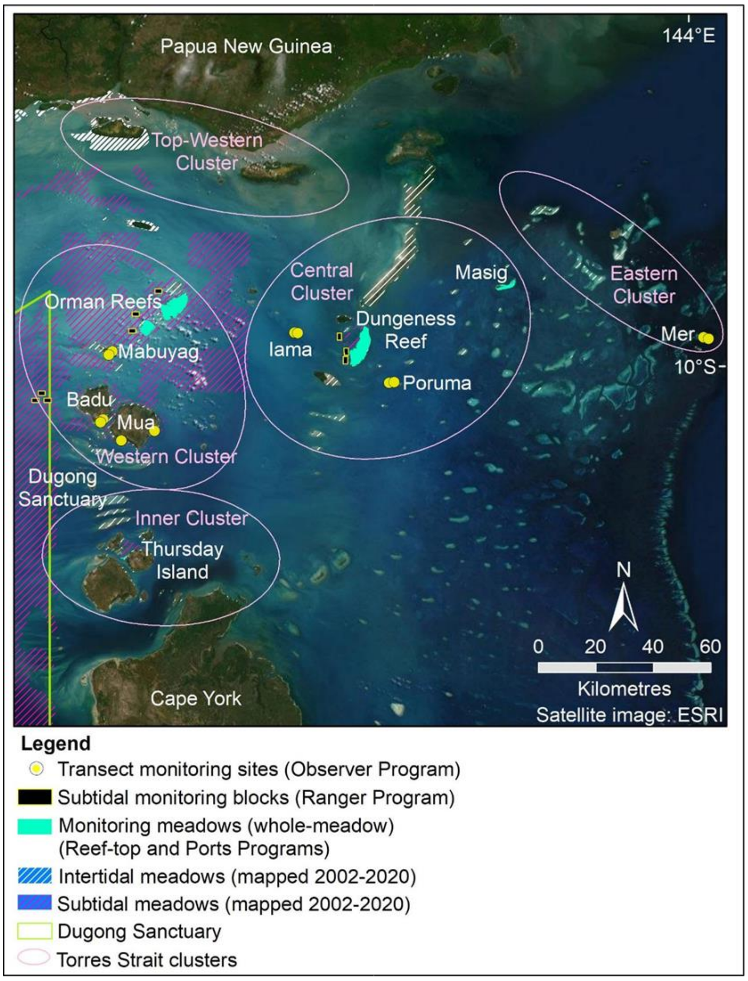

Figure 15. Map of locations where recent repeated monitoring of sea grasses occurs in Torres Strait (from Carter et al. 2022).

96) Aerial surveys by TSRA and the Australian Research Council Centre of Excellence for Coral Reef Studies documented a pronounced inshore-offshore gradient in the intensity of bleaching in 2016 due to extreme sea temperatures (Figure 16). Offshore reefs in the west remained cool, and saw little or no bleaching. A swatch of reef inshore from the edge of the continental shelf exhibited increasing levels of bleaching across a steep gradient. The central and inner regions experienced extreme levels of bleaching and massive levels of mortality. For the top quartile of reefs (i.e. the 25% of reefs that were most severely impacted) in 2016, mortality of corals following bleaching ranged from 84-99%. When mortality is this high, it affects even long-lived (normally) thermally-resistant species. The die-off of corals in 2016 in Torres Strait and the northern Great Barrier Reef – from Papua New Guinea to Cairns - was by far the largest loss of corals ever recorded (Hughes et al. 2018a). Based on limited monitoring of coral reefs since 2016, the TSRA 2021 State of Environment Report Card assessed the condition of corals reefs in the region to be “of significant concern”.

97) Mass bleaching has re-occurred in Torres Strait in 2017, 2020 and 2022 due to high temperatures, creating a spatial patchwork of responses. The geographic footprint and intensity of each bleaching event was closely matched by the observed spatial patterns in accumulated heat (See Question 7), measured by the US National Oceanic and Atmospheric Administration from satellites as Degree Heating Weeks (DHW). For example, in 2016, heating and bleaching were extreme on the inner (western) and mid-shelf region of Torres Strait, while the offshore ribbon reefs to the east did not bleach. In 2017, many of the eastern reefs (including the outermost ribbon reefs) bleached moderately in response to DHW levels that were higher than in 2016 (Hughes et al. 2021).

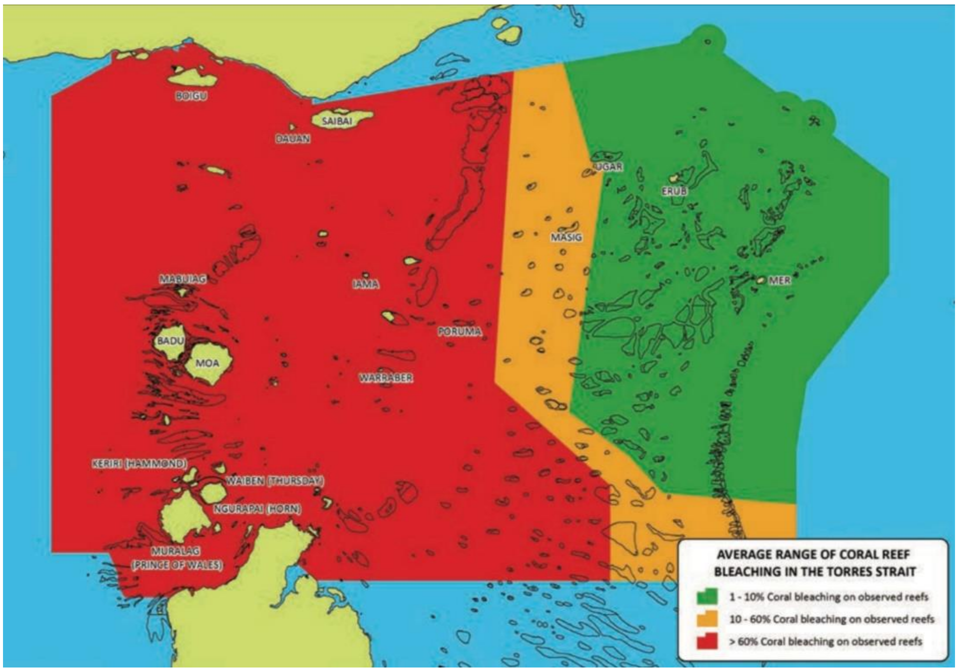

Figure 16. Extensive bleaching of coral reefs occurred across Torres Strait in early 2016 due to anthropogenic heating. (TSRA 2021).

V. CURRENT TORRES STRAIT IMPACTS

For the purposes of your response to question 6, please assume tipping points in the climate system refer to critical thresholds in components of the system, beyond which the component reorganises abruptly and sometimes irreversibly ("Tipping Points").

6. *Please identify the Tipping Points (if any) that have been reached and explain their relevance in the context of the Torres Strait Impacts.*

98) Tipping points or thresholds can occur in many dynamic systems, including elements of the Earth's climate, and in the complex responses of ecosystems, species and people to escalating climatic drivers (Question 3(a), Figure 8-10). Here, in Question 6, I focus on examples of tipping point behaviour exhibited by coral reef ecosystems and vulnerable species in Torres Strait that are associated with climate change and other anthropogenic drivers. Understanding these dynamics can help to manage and anticipate the impacts of inevitable future climate change (see Question 8).

99) The thresholds of atmospheric greenhouse gas concentrations that trigger coral bleaching at global and regional scales have been surpassed over the past four decades. Prior to the 1980s, mass coral bleaching was very rare at regional scales, even during El Nino events (when sea surface temperatures are higher at most tropical locations). Later, following an extended period of little or no mass bleaching, El Ninos gradually became more dangerous for coral reefs and other ecosystems, due to anthropogenic heating. The first, second and third global-scale bleaching events occurred in 1998, 2010 and 2015-2016 during this intermediate period. More recently, regional-scale mass bleaching is now occurring throughout ENSO cycles, including the first mass bleaching of the Great Barrier Reef (including Torres Strait) under La Nina conditions in 2022.

100) The 2016 bleaching event, the first for 14 years, triggered an unprecedented loss of corals on the northern third of the Great Barrier Reef, and to a lesser extent, the central third, with virtually no mortality further south. The geographic footprint and intensity of the coral die-off was closely matched by the observed north-south and east-east west patterns in accumulated heat (Question 7, Figure 19), measured by the US National Oceanic and Atmospheric Administration from satellites as Degree Heating Weeks (DHW).

101) Within the 1,200 km extent of the northern and central regions where moderate to severe bleaching occurred in 2016 (from 9.5-19.5^{o}S), the overall decrease in coral cover that year was 38.2%. In the northern 700 km section (from 9.5-14.5^{o}S) where the heat exposure and bleaching was the most extreme, 50.3% of the coral cover in shallow-water habitats was lost within eight months (Hughes et al. 2018a). In comparison to cyclones, the loss of corals and the area affected by the 2016 climatic event was an order of magnitude greater than the patchier damage that typically occurs on reefs sites within the track of a severe tropical cyclone (Dietzel et al. 2021a).

102) Tipping points occur in Torres Strait and elsewhere in the responses of corals to the heat exposure caused by anthropogenic heating. When the USA National Oceanographic and Atmospheric Administration (NOAA) issues a bleaching forecast, it advises that a

threshold heat exposure of 4 DHW is likely to cause mass bleaching, and exposures of 8 DHW or above is expected to trigger coral mortality. The empirical relationship between DHW exposures and observed losses of corals allows prediction of the future impacts of greenhouse gas emissions and rising temperatures on coral reefs (IPCC 2018). Each bout of extreme thermal exposure on the Great Barrier Reef in 1998, 2002, 2016, 2017 and 2020 elicited a unique, non-linear bleaching response. In each event, Degree Heating Week exposure in that summer correctly predicted the probability of severe bleaching in 82 to 90% of cases (Hughes et al. 2021).

103) However, NOAA's bleaching and mortality thresholds of 4 and 8DHW, respectively, are highly variable from one bleaching event to the next, and among locations with different bleaching histories. For example, in Torres Strait in 2016, a band of offshore reefs (the orange area in Figure 16) showed moderate bleaching in response to heat exposure of only 2 or 3DHW. Similarly, mortality of corals due to bleaching in 2016 in Torres Strait (and elsewhere on the northern Great Barrier Reef) began at 4DHW (Question 2(b), Figure 3) - substantially lower than NOAA's predicted threshold of 8DHW. The most likely reason for these disparities between the predicted and observed thresholds is the dominance of heat-sensitive coral species in Torres Strait and the rest of the Great Barrier Reef in 2016, because mass bleaching had not occurred on most individual reefs since 2002 or 1998. This long 14-16 year interval without mass bleaching meant that most reefs were dominated by heat-sensitive *Acropora* species in 2016, whereas *Acropora* were already severely depleted in Torres Strait when severe heating reoccurred in 2017.

104) In Torres Strait, it took a lot more heat stress in 2017 to trigger the same bleaching and mortality response as 2016, because most of the heat-sensitive corals were already dead. In general, when pairs of successive bleaching episodes were close together (1-3 years apart), the thermal threshold for severe bleaching increases because the earlier event has "hardened" surviving coral assemblages to further impacts (Hughes et al. 2021). Dead corals do not bleach again. Consequently, bleaching in 2017 of *Acropora*-dominated corals on the central and southern Great Barrier Reef occurred at a much lower threshold of heat exposure compared to Torres Strait (Figure 17). In 2017, 2020 and 2022, it was often impossible to score the extent of bleaching during aerial surveys of the inner (western) third of Torres Strait, because coral cover was too low following the unprecedented die-off in 2016.

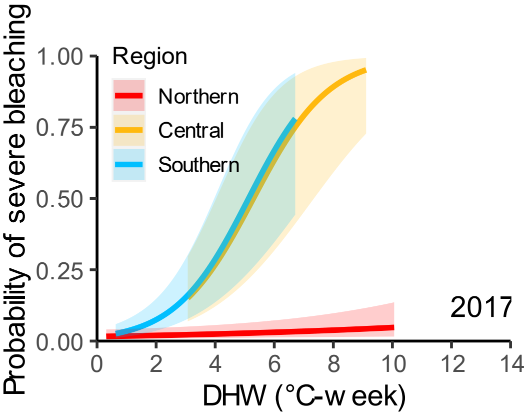

Figure 17. Regional variation in mass bleaching responses of corals on the Great Barrier Reef, in 2017. The x-axis is heat exposure, measured as Degree Heating Weeks (ºC-weeks), experienced by individual reefs. The y-axis is the resulting probability of severe bleaching measured from aerial bleaching surveys.

105) In theory, the principles underpinning the 4 and 8DHW thresholds for predicting coral bleaching and mortality could be extended to other species and ecosystems, e.g. to predict and map the physiological stress and elevated mortality of seagrass beds or mangroves that are induced by threshold levels of heat stress. However, these tools are not yet operational.

106) *Vulnerable species*: A demographic tipping point occurs when birth rates are consistently exceeded by death rates, leading eventually to regional and global extinction. Long lived species such as dugong and turtles are particularly vulnerable to population declines caused by climate change. For example, dugong take approximately 9 years to reach sexual maturity, females usually produce only one offspring after a gestation period of 13-15 months which they lactate for over a year (Welsh and Johnson 2013). Females give birth on average only every 3-7 years. These life history traits mean that even small increases in mortality and/or decreases in birth rates can lead over time to regional and global extinction. The dietary specialization of dugongs and green turtles on seagrasses and other plants is another source of vulnerability to climate change. In Torres Strait, spikes in dugong mortality and a decline in reproductive condition have both been reported following die-offs of seagrass beds. The replenishment of saltwater crocodile and turtle populations is threatened by further feminization of hatchlings, even if mortality of juveniles and adults from local stressors is stabilized or improved.

107) *Extinction:* The extinction of a species represents an irreversible tipping point (Question 2(c)). The first recorded extinction in Australia of a mammal species due to climate change, was declared by IUCN in 2015: *Melomys rubicola*, endemic to Bramble Cay (Maizab Kaur) in northern Torres Strait (Question 4). In the decade preceding its extinction, > 90% of the vegetation of the cay was destroyed by sea water inundation due to storm surges and rising sea level. Bramble Cay, similar to many other cays in Torres Strait, has a maximum elevation of just 1m above current sea level. *Melomys rubicola* was particularly vulnerable to extinction because (a) its exposure to sea level rise, (b) its tiny geographic range, with limited food supply and no possibility of being rescued by migrants from elsewhere, and (c) its small population size on one island.

7. *Assuming that the increase in global average surface temperature is presently 1.2°C (defined by decadal average) ("Current Warming Level") above a defined baseline level ("Baseline"), please explain how marine life in Torres Strait has been impacted by the Current Warming Level, by reference to the Torres Strait Impacts*.

108) In addressing Question 7, I return to the Outstanding Universal Values (OUV) framework that Australia and UNESCO routinely employ to quantify changes in the status of iconic places and ecosystems (see Paragraphs 9-15). My focus here is on the effects of the "Current Warming Level" on the current condition of coral reefs in Torres Strait, because (a) reefs play a key role in defining all relevant OUV metrics, and (b) there is substantially more information available for coral reefs and their responses to climate change than any other tropical marine ecosystem. The responses to Climate Change Impacts of seagrasses, mangroves, turtles, dugongs and other habitats and species in Torres Strait (Torres Strait Impacts) are described in Question 4 and 5.

109) According to IUCN, "*Regrettably, a number of Values for which the Great Barrier Reef was inscribed on the World Heritage List have been declining significantly. There has been a further dramatic decline as a result of the 2016, 2017 and 2020 coral bleaching events….In addition to the decline in coral cover and other impacts caused by the bleaching events, ongoing declines have also been noted across a range of other attributes comprising the site's OUV, as evidenced by the declining trends in loggerhead, hawksbill and northern green turtle populations and scalloped hammerhead shark, deteriorating trends in many seabird populations and possible declines in some dolphin species. Many important processes underpinning the complexity of the Great Barrier Reef have also been declining as a result of climate change, including reef building and recruitment*" (IUCN World Heritage Outlook 2020).

110) To be included on the World Heritage List, sites must be of Outstanding Universal Value (OUV) and meet specific criterial for listing. Corals make a substantive contribution to OUV for all four of the natural criteria for World Heritage invoked in 1981 for listing of the Great Barrier Reef: (1) significant geomorphic features, (2) significant ongoing ecological and biological processes, (3) significant natural habitats for the conservation of biological diversity, and (4) exceptional natural beauty.

111) *Significant Geomorphological Features*: Torres Strait contains one of the widest range of reef types in the world, including extensive inshore turbid reefs, fringing reefs on high islands, wooded cays, mid-shelf reefs, ribbon reefs, deltaic reefs, submerged shoals, *Halimeda* bioherms, and mesophotic (deep) reefs. These reefs represent major stages in the Earth's evolutionary history and meet the criterion of unique Outstanding Universal Value. Coral bleaching in Torres Strait due to anthropogenic heating associated with 1.2°C of global average warming has already substantially affected shallow reef-building processes, such as internal and external bioerosion, calcification and reef accretion.

112) *Significant ongoing ecological and biological processes*: Episodic heavy losses and a gradual long-term decline in corals in Torres Strait will profoundly change virtually all reef processes. For example, particle feeding by corals in Torres Strait has declined, predation on them has increased (on a per-capita basis), disease of stressed corals is likely increasing,

and recruitment of corals has been impaired (Figure 7). Other key processes that have been affected so far by 1.2^{o}C of global average warming are symbiosis between corals, zooxanthellae and microbes, competition for space, herbivory, calcification, and the provision of coral habitat. Ecological processes provided by heat-sensitive coral species are particularly vulnerable to ongoing anthropogenic heating. For example, the decline of branching *Acropora* and *Pocillopora* corals in Torres Strait reduces the provision of small-scale habitat for species that depend on live corals, including many reef fishes and invertebrates (Hughes et al. 2018b).

113) *Significant natural habitats for the conservation of biological diversity*: Corals form a network of interconnected coral reefs throughout Torres Strait, and >400 species of hard coral that create the habitat that supports biodiversity of all reef-associated species throughout the region. Reef environments (generated by settlement, growth and accretion by corals) also support reef-dependent industries [redacted] in Torres Strait. Climate change, particularly losses of corals in 4 major bleaching events since 2016, has already eroded these key attributes.

114) *Exceptional natural beauty*: Corals provide superlative natural beauty and spectacular underwater scenery[redacted]. Natural phenomena include annual coral spawning and significant spawning aggregations of many fish species that depend on corals for habitat, particularly during their juvenile phase. The widespread loss of coral cover in shallow-water habitats of Torres Strait following coral bleaching events associated with 1.2^{o}C of global average warming has already substantially diminished aesthetic values.

115) Fewer than 2% of the 573 individual reefs that were repeatedly assessed along the Great Barrier Reef during bleaching events in 2016, 2017 and 2020 escaped bleaching entirely during those three latest events (Figure 18). So far, almost all reefs that have escaped with minimal or no bleaching since 1998 are located in a single aggregation, approximately 200-250 km offshore, close to latitude 22^{o}S on the southern Great Barrier Reef (Figure 18, 19). This area has remained consistently cool during summer months (<4 ^{o}C-weeks) during all previous mass bleaching events (Figure 18), possibly due to tidal movements and upwelling at the edge of the continental slope. However, other offshore upwelling areas with episodic intrusion of cool water in Torres Strait, the northern and southern Great Barrier Reef have experienced unusually warm summer periods and severe bleaching repeatedly since 1998 (Figure 18), suggesting that favorable hydrodynamic conditions are intermittent, and may not always coincide with extended periods of hot summer temperatures.

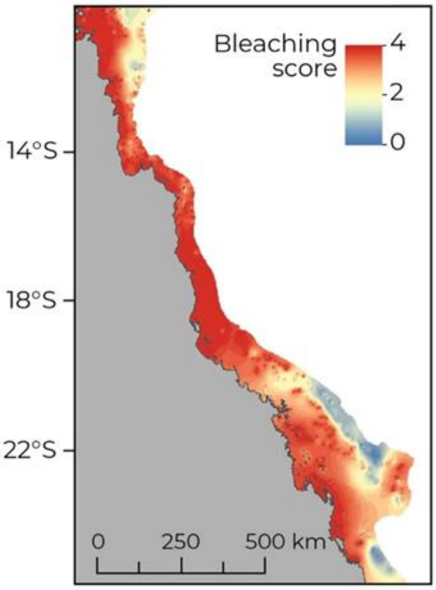

Figure 18. Map of the Great Barrier Reef, including Torres Strait, showing the maximum bleaching scores during three mass coral bleaching events in 2016, 2017 and 2020, measured by repeated aerial surveys of 573 reefs. Bleaching scores are 0 (<1% of corals bleached), 1 (1-10%), 2 (10-30%), 3 (30-60%), 4 (>60%). Dark blue indicates small areas that escaped heat stress and bleaching in all three events (Hughes et al. 2021).

116) Figure 18 shows that the extent of spatial refuges from coral bleaching – locations that could potentially re-seed nearby damaged reefs in future decades - has steadily declined on the Great Barrier Reef. Following the latest mass bleaching in 2022, only 1.7% of individual reefs (spanning fourteen degrees of latitude) have escaped with no bleaching since 1998 (Figure 19). Even the most stringent marine protected areas have bleached severely, and there is little evidence that deeper, mesophotic reefs are a source of resilience for species that primarily occur in shallower habitats. Following the sixth event in 2022, regions and reefs that were earmarked earlier as candidate refuges have now also experienced severe or moderate bleaching at least once. For example, Torres Strait escaped with little bleaching in 1998 and 2002, before experiencing very severe bleaching in 2016. Offshore areas of Torres Strait that did not bleach in 2016 were moderately bleached in 2017 (Figure 18, 19).

117) While coral populations have been repeatedly damaged by recurrent severe bleaching episodes, diminished adult brood stock still persist throughout Torres Strait and the Great Barrier Reef more broadly, even after six bleaching events. Recurrent climate extremes have generated an increasingly complex mosaic of reefs and sites within reefs with different histories of bleaching. Given the low to modest dispersal capacity of coral larvae compared to many marine invertebrates and fishes, the remaining unbleached southern reefs (Figure 19), which lie downstream from the rest of the Great Barrier Reef including Torres Strait, are unlikely to make a demographically significant contribution of replenishment of other reefs spread for >2,000km to the north. The multi-decadal accumulation of bleaching impacts (Figure 18) highlights the grave risk that without immediate global action on

greenhouse gas emissions, more frequent and more severe bleaching events will continue to undermine the resilience of coral reef ecosystems in Torres Strait and elsewhere.

118) Coral reefs in Torres Strait have already been permanently damaged by anthropogenic heating that triggered repeated die-offs since 2016. The distinctive geographic footprints of recurrent coral bleaching in Torres Strait and on the Great Barrier Reef in 1998, 2002, 2016, 2017, 2020 and 2022 have been documented by six detailed aerial surveys. In each event, the extent and severity of bleaching has been determined by the spatial pattern of anomalously high sea temperatures in each year (Figure 19). In Torres Strait, bleaching was particularly severe in 2016 and to a lesser extent in 2017 and 2020. Prior to catastrophic losses of corals in Torres Strait due to bleaching in 2016, coral reefs were assessed as being in “good” condition in 2015. However, after repeated episodes of mass coral bleaching, the 2021 condition for coral reefs was assessed as of ‘significant concern’ (TSRA 2021).

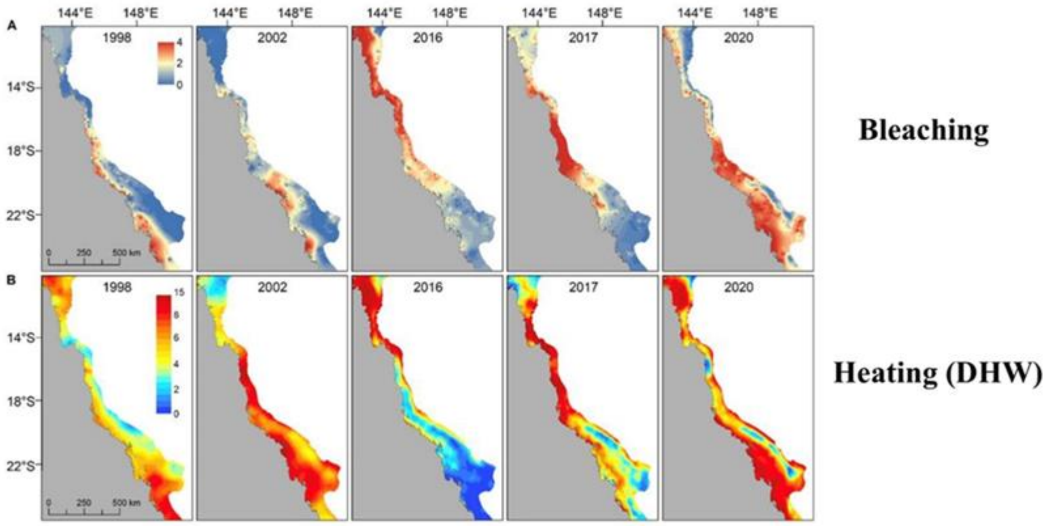

Figure 19. (A) Geographic extent and severity of coral bleaching in Torres Strait and on the Great Barrier Reef during major events in 1998, 2002, 2016, 2017 and 2020, measured by extensive aerial scores: 0 (<1% of corals bleached), 1 (1-10%), 2 (10-30%), 3 (30-60%), 4 (>60%). The number of reefs surveyed in each year was 587 (in 1998), 630 (2002), 1,135 (2016), 742 (2017) and 1,036 (2020). (B) Spatial pattern of heat stress (Degree Heating Weeks, °C-weeks) measured from satellites during each mass bleaching event. Dark blue represents 0 °C-weeks and red is 15 °C-weeks (the maximum recorded, in 2017 and 2020). (Hughes et al. 2021).

- In 1998, bleaching was primarily coastal and most severe in the central and southern regions of the Great Barrier Reef. Torres Strait was largely unaffected.

- In 2002, bleaching was more widespread, and affected offshore reefs in the central region that had escaped bleaching in 1998. Torres Strait escaped significant bleaching for a second time.

- In 2016, bleaching was even more extensive and much more severe, especially in Torres Strait and the northern Great Barrier Reef, and to a lesser extent the central region, where many coastal, mid-shelf and offshore reefs were affected (Figure 5). In 2016, the proportion of reefs experiencing extreme bleaching (defined as >60% of corals bleached) was over four times higher compared to 1998 or 2002. Conversely, in 2016, only 8.9% of surveyed reefs escaped with no bleaching, compared to 42.4% in 2002 and 44.7% in 1998.

- In 2017, bleaching and heat intensity were most severe in the central region. Torres Strait experienced a second year of bleaching which was less intense than in 2016. This was the first occurrence of back-to-back bleaching in two consecutive summers.

- In 2020, prolonged hot conditions occurred simultaneously in the northern, central and southern regions for the first time. Bleaching was most severe in the southern region, which had escaped bleaching in 2016 and 2017. Inner parts of Torres Straits bleached again.

- In 2022, heating and coral bleaching were most severe in the central region, a similar geographic pattern to 2017: https://www.gbrmpa.gov.au/the-reef/reef-health/_nocache.

119) The responses of corals to heat exposure varies significantly among species. In the aftermath of each mass bleaching event, many reefs have shifted away from the dominance of heat-sensitive, fast-growing, three-dimensional, branching and tabular species with dense skeletons, to a depauperate assemblage dominated by heat resistant corals with simpler morphological characteristics and slower growth rates (Hughes et al. 2018b; Great Barrier Reef Outlook Report 2019). This spectrum of responses is most pronounced when and where bleaching is mild. In contrast, when heat exposure and bleaching stress are severe, even heat-resistant corals exhibit high rates of mortality.

120) In 2016, when bleaching in Torres Strait was extreme, the abundances of all categories of corals decreased to varying degrees on heavily bleached reefs (defined as reefs with >60% of colonies). Declines of >75% were exhibited by tabular and staghorn *Acropora, Seriatopora hystrix* and *Stylophora pistillata* - fast-growing, branching, weedy species that dominate many shallow Indo-Pacific reefs (Figure 20). Losses of these heat sensitive species sharply reduced the three-dimensionality of reef surfaces – the nooks and crannies that harbour the iconic biodiversity of coral reefs, including the juveniles of commercially important reef fisheries. In comparison, heat-resistant corals tend to be encrusting or dome-shaped, and are poor providers of micro-habitat. This widespread shift in the mix of coral species has impacted the heritage values of Torres Strait and the Great Barrier Reef World Heritage Area (WHA) because individual species contribute differently to numerous ecological functions and processes.

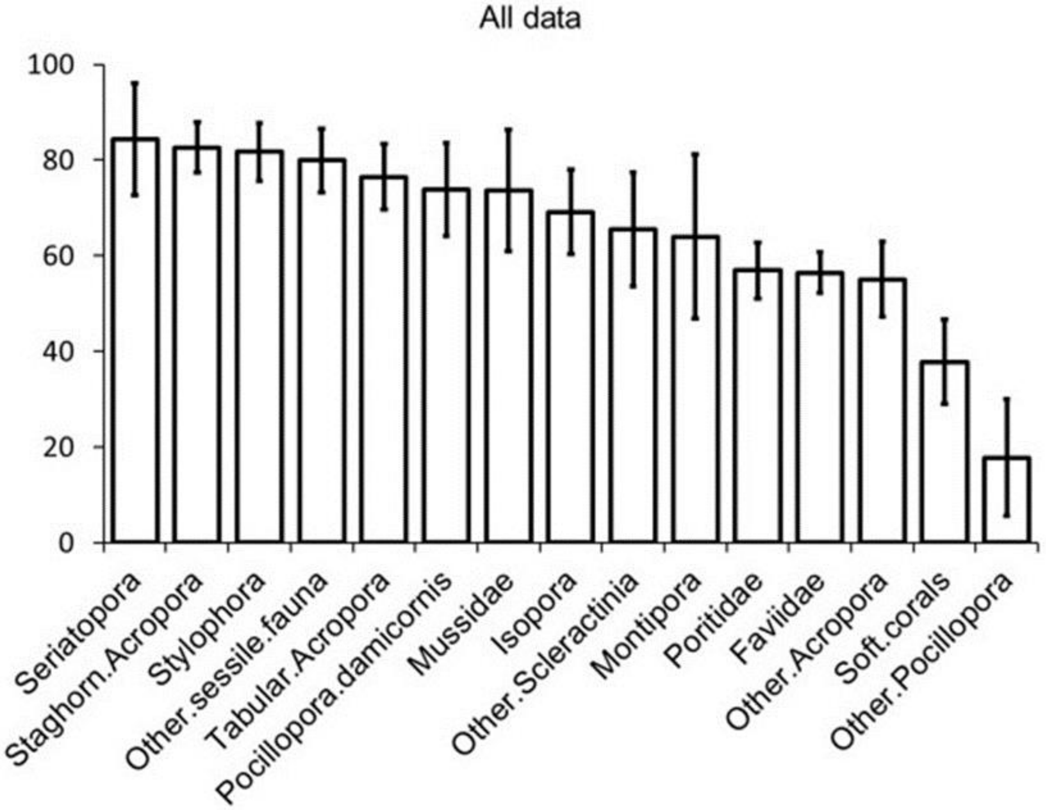

Figure 20. Mortality rates due to coral bleaching differ among species and genera. Average loss of cover for taxonomic categories recorded on 63 reefs with >60% bleaching, between March and November on 63 re-censused reefs with >60% bleaching. Taxa are plotted in rank order along the x-axis from high to low decreases in cover, illustrating a spectrum of comparatively resistant species on the right and more sensitive species to the left. Error bars are one standard error (Hughes et al. 2018b).

VI. PROJECTED TORRES STRAIT IMPACTS

8. Please explain how you would expect marine life in the Torres Strait to be impacted in the future if the global average surface temperature continues to increase beyond the Current Warming Level, by reference to the Torres Strait Impacts and any relevant Climate Impacts as defined in Annexure B to the Preliminary Letter of Instruction. For the purpose of writing your report, and in answering both questions 7 and 8 of your instructions, please assume that the relevant Baseline is 1850-1900 (or 'pre-industrial levels' as adopted in the IPCC's Sixth Assessment Report).

121) I address this question by considering two scenarios – global average warming of 1.5°C and 2°C above the pre-industrial baseline. As in Question 7, I focus here on coral reefs because they are particularly heat-sensitive (Figure 19a), and have been the focus of extensive modelling studies (IPCC 2018). The original species composition of corals in Torres Strait will be permanently changed and irrecoverable under a temperature rise of 1.5°C above pre-industrial levels. Loss of adult brood-stock will lead to widespread recruitment failure and diminished connectivity of larvae. The IPCC (2018) concluded that *"Multiple lines of evidence indicate that the majority (70–90%) of warm water (tropical) coral reefs that exist today will disappear even if global warming is constrained to 1.5°C (very high confidence)* {3.4.4, Box 3.4}."

122) Coral reefs throughout the tropics will continue to degrade over the current century until climate change stabilises, allowing remnant populations to reorganize into remnant, heat-tolerant reef assemblages, or immature assemblages that can exhibit limited recovery between future bleaching events. The 2016, 2017, 2020, and 2022 mass bleaching events in Torres Strait have already triggered the initial phase of that transition. The process of recovery of corals after each bout of mass bleaching – the replacement of dead corals by new ones – is slowing down (Ortiz et al 2018), and increasingly on reefs worldwide, a recovery trajectory is truncated by each new coral bleaching event (Figure 12). According to IPCC (2018): *Restricting overall warming to 1.5°C will still see a downward trend in average coral cover (70–90% decline by mid-century) but will prevent the total loss of coral reefs projected with warming of 2°C.*

123) Longer-term impacts of anthropogenic climate change in Torres Strait over the next decade will also likely include higher levels of disease in corals, heat stress in most species, and lower rates of reproduction. These trends are already underway – for example, the feminization of turtle hatchlings (Jensen et al. 2018), elevated diseases in turtles, corals and sea grasses and crashes in coral recruitment following die-offs of adult brood stock due to temperature extremes (Figure 7). The per capita predation rate on corals will rise, because there will be more predators per coral (e.g. the snail *Drupella*, and crown of thorns starfish *Acanthaster*). Loss of corals will have far-ranging impacts on fish and other organisms that depend on them for food and shelter (Question 4).

124) The increased patchiness and erosion of Integrity of Torres Strait and the broader Great Barrier Reef will continue to accelerate with further warming. Already, after six bouts of mass coral bleaching in the past 25 years, only 1.7% of the Great Barrier Reef remains unbleached, and 80% has bleached severely (with associated loss of corals) at least once

since 1998 (Question 7, Figure 19). Warming of 1.5°C will cause more damage than the current level of anthropogenic heating (approximately 1.2°C so far), and 2°C or higher will be much worse – because the relationship between further heating and ecological, social and economic impacts is not linear - it accelerates.

125) A dwindling proportion of relatively intact habitats (e.g. mangroves, sea grass beds, corals reefs) in Torres Strait will be critical for a long-term recovery - if global temperatures remain below or close to the 1.5°C Paris target. As noted by IPCC (2018) for coral reefs: *"The remaining reefs at 1.5°C will benefit from increasingly stable ocean conditions by the mid-to-late 21st century. Limiting global warming to 1.5°C during the course of the century may, therefore, open the window for many ecosystems to adapt or reassort geographically."*

126) Every fraction of a degree of further warming causes further severe impacts, as shown for example by the relationship between Degree Heating Weeks and coral bleaching (Figures 3 and 9). In its comparison of the impacts of 1.5°C versus 2°C on coral reefs, the IPCC stated: *Even achieving emissions reduction targets consistent with the ambitious goal of 1.5°C of global warming under the Paris Agreement will result in the further loss of 70–90% of reef-building corals compared to today, with 99% of corals being lost under warming of 2°C or more above the pre-industrial period.* (IPCC 2018). These growing impacts, including the escalating effects of anthropogenic heating on the Great Barrier Reef, illustrate the non-linear effects of each incremental increase in temperature.

127) The erosion of integrity of the Great Barrier Reef (including Torres Strait) will continue to accelerate with further warming. Above warming of 1.5°C, the few remaining patches of unbleached reefs (Figure 19) will continue to shrink and become more fragmented. Torres Strait and the broader Great Barrier Reef will become more uniformly degraded. The dwindling proportion of relatively intact reefs will make a diminishing contribution to the production and dispersal of coral larvae. Without fewer relatively-intact sources of larvae, damaged reefs will remain degraded for longer if temperatures equilibrate well above the upper 2°C Paris target.

128) A rise in temperature of 2°C above the pre-industrial global average is likely to result in the Great Barrier Reef and all other coral reef World Heritage Areas being de-listed by UNESCO, due to the loss of OUV of reefs everywhere. Already, with 1.2°C of warming so far, many elements of the Great Barrier Reef's OUV have declined from *'very good'* to *'good'* or *'poor'* (Table 1). The non-linear responses of many biological systems to increased warming (e.g. Figure 9) will ensure that the impacts of 2°C will be much greater than 1.5°C (Question 3 of this report).

129) According to IPCC (2018): *A world in which global warming is restricted to 1.5°C above pre-industrial levels would be a better place for coral reefs than that of a 2°C warmer world, in which coral reefs would mostly disappear*. The lowest (most optimistic) emissions scenario repeatedly assessed by the IPCC is Representative Concentration Pathway, RCP2.6, in which emissions peak during the decade 2010-2020 and achieve the limit of well below 2°C by 2100. Even if the 2°C Paris Agreement target is achieved through an emissions pathway similar to RCP2.6, this projected level of warming will have

very severe consequences for coral reefs, particularly when temperatures spike above long-term summer maxima, leading to recurrent bleaching events. According to climate modelling commissioned by UNESCO, *holding the increase in the global average temperature to well below 2°C above pre-industrial levels…. is essential to secure a sustainable future for World Heritage-listed coral reefs* (Heron et al. 2018).

130) Torres Strait is projected by climate models to bleach twice each decade from 2035, and to bleach annually after 2044 under a scenario of business-as-usual greenhouse gas emissions (Heron et al. 2018). The benchmark of two bleaching events every ten years has already been breached twice in 2016-2022, and the first instance of back-to-back bleaching in two consecutive years occurred in Torres Strait in 2016 and 2017 (Figure 19).

131) The current disparities in the condition of coral reefs in different parts of Torres Strait and the Great Barrier Reef more broadly are likely to diminish under a 2^{o}C scenario. Spatial refuges - areas that have not yet bleached (or which may remain unbleached or lightly bleached with warming of 1.5^{o}C) are expected to disappear. According to IPCC's assessment: *Reaching 2°C will increase the frequency of mass coral bleaching and mortality to a point at which it will result in the total loss of coral reefs from the world's tropical and subtropical regions* (IPCC 2018). On the Great Barrier Reef as a whole, spatial refuges from bleaching are greatly diminished following six events since 1998, and are now restricted to a small, offshore area in the southern Great Barrier Reef (the dark blue colouring in Figure 18).

The heritage values and OUV of Torres Strait;

132) According to UNESCO's global assessment of coral bleaching on all World Heritage reef properties, it is clear that limiting global average temperature increase to 1.5°C above pre-industrial levels is an essential action to secure their protection, give them the chance to persist in a changing climate, and continue providing benefits to associated human communities (Heron et al. 2018). The ongoing loss of corals under a 2^{o}C scenario will severely undermine their key contribution to OUV for all of the natural criteria for World Heritage listing of the Great Barrier Reef: (1) significant geomorphic features, (2) significant ongoing ecological and biological processes, (3) significant natural habitats for the conservation of biological diversity, and (4) exceptional natural beauty.

133) *Significant Geomorphological Features*: Torres Strait contains one of the widest ranges of reef types in the world, including extensive inshore turbid reefs, fringing reefs on high islands, wooded cays, mid-shelf reefs, ribbon reefs, deltaic reefs, submerged shoals, and mesophotic (deep) reefs. A 2^{o}C warming scenario, and associated ocean acidification, would substantially impede shallow reef-building processes, such as internal and external bioerosion, calcification and reef accretion. Without abundant corals, bioerosion will exceed calcification, leading to negative net accretion and the gradual loss of geomorphological features.

134) *Significant ongoing ecological and biological processes*: A 2^{o}C scenario resulting in episodic heavy losses and a severe long-term decline in corals will profoundly change virtually all reef processes. For example, particle feeding by corals will decline, per-capita

predation on them will increase and recruitment of corals will be severely impaired by the decline of adult brood stocks. Other key processes that will be affected include coral symbiosis, competition for space, herbivory, calcification, and the provision of coral habitat.

135) *Significant natural habitats for the conservation of biological diversity*: Corals generate key habitats that support biodiversity throughout Torres Strait. A 2°C scenario would destroy most coral habitat. Reef environments (generated by settlement, growth and accretion by corals) also support reef-dependent industries [redacted] (Great Barrier Reef Outlook Reports, 2009, 2014, 2019), which would all severely decline under a 2°C scenario.

136) *Exceptional natural beauty*: Corals provide superlative natural beauty and spectacular underwater scenery [redacted]. The widespread loss of coral cover in shallow-water habitats following coral bleaching events has already substantially impacted on aesthetic values. A 2°C scenario would destroy most corals, leading to a severe loss of natural beauty.

137) Because of the vulnerability of coral reefs to extreme temperatures, a short period of overshoot above the temperature goals of 1.5°C or 2°C would be extremely damaging to Torres Strait. Furthermore, ecological impacts of anthropogenic heating during an overshoot period would likely last for at least several decades and may not be reversible. Climate models project a 70-90% decline in coral cover globally with 1.5°C of warming, and a 99% decline if global average temperatures reach 2°C above pre-industrial levels. An overshoot would exceed these projected levels of damage. (IPCC 2018).

138) Attempts to restore diminished coral cover through coral gardening, assisted migration (by harvesting larvae) and assisted evolution (rearing corals in an aquarium) are prohibitively expensive and unworkable at any meaningful scale (Condie et al. 2021). Some forms of rehabilitation of assemblages of corals, sea grasses and mangroves may be feasible, affordable and ethical - using currently available methods and capabilities - for very small areas (typically <<1 km2) of high economic value, such as tourist sites. Re-building populations of corals is far more expensive than repairing other, more accessible and less biodiverse marine ecosystems, or terrestrial vegetation. For example, the median cost per hectare for coral gardening is estimated to be >60 times higher than for restoring intertidal mangroves, and >90 times higher than for sea grasses. Restoration typically focusses on rebuilding depleted populations of a small number of fast-growing species at local scales, and does not restore biodiversity or reverse regional-scale declines. Consequently, the only lasting solution for sustainable protection of structurally important species in Torres Strait and elsewhere is a rapid reduction in global emissions of greenhouse gasses.

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PHI x FINNEY x MCDONALD

31 January 2023

PRIVILEGED AND CONFIDENTIAL

Professor Terry Hughes

By email: [redacted]

Dear Professor Hughes,

Pabai & Anor v Commonwealth of Australia (VID622/2021) (Proceeding)

---

1. Letter of Instruction

1.1. We refer to our letter of retainer dated 15 December 2022 (**Retainer Letter**) and confirm that you are retained by Uncle Pabai Pabai and Uncle Paul Kabai (**Applicants**) to act as an independent expert in the matter of *Pabai & Anor v Commonwealth of Australia*, VID622/2021 (**Proceeding**).

1.2. We confirm that the confidentiality obligations in respect of documents and information provided to you for the purpose of this engagement are governed by the terms of the Retainer Letter and Deed of Confidentiality dated 15 December 2022.

1.3. We also remind you of the roles and duties of expert witnesses as set out in the Retainer Letter and ask that you refer to them as you prepare your expert report(s) in the Proceeding. In particular, please take some time to reacquaint yourself with the following documents, which we provided to you with our original letter:

(a) the Federal Court of Australia Expert Evidence Practice Note (**GPN-EXPT**), including the Harmonised Expert Witness Code of Conduct (the **Code**) at Annexure A of that Practice Note and the Concurrent Expert Evidence Guidelines (the **Guidelines**) at Annexure B (collectively, the **Practice Note**); and

(b) Rule 23.13 of the *Federal Court Rules 2011* (Cth).

1.4. The purpose of this letter is to request that you commence preparing a written report, providing your independent expert opinion, in response to the preliminary questions outlined at Annexure B to this letter.

1.5. We note that a further set of questions to be addressed in your report, in addition to those set out at Annexure B, will be provided shortly.

2. Brief of Materials

2.1. Set out at Annexure A is an index of the documents provided to you, which form your brief. If you would prefer to receive a copy of some or all of the Annexure A documents in hard copy, please do not hesitate to contact us with such a request.

2.2. If you consider that you require any additional documents or materials in order to complete your work, please request such materials from us.

3. Your Opinion

3.1. Once you have reviewed the material in your brief, we request that you commence drafting a written report addressing the preliminary questions set out in Annexure B to this letter.

3.2. Once you have received the further set of questions referred to at 1.5 above, we request that you provide a written report.

3.3. In answering the questions, please provide detailed reasons for your opinions, including the facts or assumptions that affect your reasoning and conclusions, with specific reference to any of the material listed in Annexure A on which you rely in reaching your conclusions.

4. Preparation of Your Report

4.1. We would be grateful if you would set out the answers to the questions in a written report, having regard to the requirements set out in the Federal Court of Australia Expert Evidence Practice Note.

4.2. After you have had the opportunity to consider the questions at Annexure B, as well as the materials listed in Annexure A, we would be grateful if you could advise of any material not currently in your brief which you require to respond to any of the Annexure B questions.

If you have any questions, please do not hesitate contact me [redacted]

Yours faithfully,

Brett Spiegel
Principal Lawyer
Phi Finney McDonald

Encl.

ANNEXURE A

Index to Brief

Tab No.	Date	Description of document(s) / category
A	**LETTERS OF INSTRUCTION**	
A1.	31 January 2022	Letter of instruction
B	**PLEADINGS**	
B1.	7 October 2022	Amended Originating Application
B2.	12 August 2022	Amended Statement of Claim
B3.	21 September 2022	Defence to Amended Statement of Claim

ANNEXURE B

Basis of Expertise

1. Please describe your academic qualifications and professional background, your experience in the field of climate change impacts to marine life (including, in particular, in the Torres Strait) and any other training, study or experience that is relevant to this brief. You may wish to do so by reference to a current curriculum vitae.

Climate Science Assumptions

For the purposes of your answers to the questions below, please assume that the following matters are impacted by climate change:

i) global average surface temperature (calculated from both land and ocean temperatures);

ii) ocean surface temperature;

iii) ocean acidification;

iv) rising sea levels; and

v) the frequency, size and intensity of extreme weather events, including heatwaves, droughts, tropical cyclones, severe storms and heavy rainfall (as well as associated flooding)

(together, **"Climate Impacts"**).

Climate Impacts

2. Please identify and explain the relationship between the Climate Impacts and the following aspects of marine life:
    a) mangroves and coastal wetlands;
    b) coral bleaching events;
    c) marine species, including by reference to the risk (if any) of particular species becoming endangered, more critically endangered and/or extinct;
    d) biodiversity in flora and/or fauna, as distinct from the impact to any particular species;
    e) marine ecosystems, including by reference to processes such as the spread of disease and the incidence of pathogens; and
    f) any other aspect of marine life that you consider has a relevant relationship with the Climate Impacts

    (together, **"Marine Life Impacts"**).

3. In addressing the relationship between the Climate Impacts and the Marine Life Impacts, please also:
    a) identify and explain the extent (if any) to which the Marine Life Impacts may have a corresponding effect on the Climate Impacts (for example, by way of reinforcing feedbacks);
    b) explain whether the relationship between each relevant Climate Impact and each relevant Marine Life Impact is linear or non-linear; and

c) explain whether there is any variation geographically (that is, whether the relevant Climate Impact affects the relevant Marine Life Impact in the same way and to the same extent everywhere around the world).

Marine Life Impacts in the Torres Strait

4. Please identify which of the Marine Life Impacts (if any) are of particular significance to marine life in the Torres Strait (**"Torres Strait Impacts"**), including by reference to:
   a) relevant species of flora (such as seagrass) and fauna (such as lobsters, green turtles, dugongs); and
   b) relevant aspects of biodiversity.
5. In respect of each of the Torres Strait Impacts, please:
   a) specify whether that impact is relevant to the whole of the Torres Strait; or
   b) identify that part of the Torres Strait to which the identified impact is relevant (for example, by reference to a specific island)

   and explain how the identified impact is relevant in that context.

Current Torres Strait Impacts

For the purposes of your response to question 6, please assume tipping points in the climate system refer to critical thresholds in components of the system, beyond which the component reorganises abruptly and sometimes irreversibly (**"Tipping Points"**).

6. Please identify the Tipping Points (if any) that have been reached and explain their relevance in the context of the Torres Strait Impacts.
7. Assuming that the increase in global average surface temperature is presently 1.2°C (defined by decadal average) (**"Current Warming Level"**) above a defined baseline level (**"Baseline"**), please explain how marine life in the Torres Strait has been impacted by the Current Warming Level, by reference to the Torres Strait Impacts.

Please note that we will provide you with a series of further questions and assumptions in relation to projected Torres Strait Impacts shortly.

PHI x FINNEY x MCDONALD

15 March 2023

PRIVILEGED AND CONFIDENTIAL

Professor Terry Hughes

By email: [redacted]

Dear Professor Hughes,

Pabai & Anor v Commonwealth of Australia (VID622/2021) (Proceeding)

---

1. Supplementary Letter of Instruction

1.1. We refer to our letter of retainer dated 15 December 2022 (**Retainer Letter**) and our preliminary letter of instruction dated 31 January 2023 (**Preliminary Letter of Instruction**) and confirm that you are retained by Uncle Pabai Pabai and Uncle Paul Kabai (**Applicants**) to act as an independent expert in the matter of *Pabai & Anor v Commonwealth of Australia*, VID622/2021 (**Proceeding**).

1.2. We confirm that the confidentiality obligations in respect of documents and information provided to you for the purpose of this engagement are governed by the terms of the Retainer Letter and Deed of Confidentiality dated 15 December 2022.

1.3. We also remind you of the roles and duties of expert witnesses as set out in the Retainer Letter and ask that you refer to them as you prepare your expert report(s) in the Proceeding. In particular, please take some time to reacquaint yourself with the following documents, which we provided to you with our original letter:

(a) the Federal Court of Australia Expert Evidence Practice Note (**GPN-EXPT**), including the Harmonised Expert Witness Code of Conduct (the **Code**) at Annexure A of that Practice Note and the Concurrent Expert Evidence Guidelines (the **Guidelines**) at Annexure B (collectively, the **Practice Note**); and

(b) Rule 23.13 of the *Federal Court Rules 2011* (Cth).

1.4. As foreshadowed in paragraph 1.5 of the Preliminary Letter of Instruction, the purpose of this supplementary letter of instruction is to provide a further question and assumption to be addressed in your written report. We request that you continue preparing a written report, providing your independent expert opinion, in response to the question and assumption outlined in Annexure B to this letter **in addition** to those provided in the Preliminary Letter of Instruction.

2. Brief of Materials

2.1. Set out at Annexure A is an index of the documents provided to you, which, **in addition** to those provided in the Preliminary Letter of Instruction, form your brief.

2.2. If you would prefer to receive a copy of some or all of the Annexure A documents in hard copy, please do not hesitate to contact us with such a request.

3. Your Opinion

3.1. Once you have reviewed the additional documents in your brief, we request that you continue drafting a written report addressing the questions set out in Annexure B to this supplementary letter and Annexure B to your Preliminary Letter of Instruction.

3.2. In answering the questions, please provide detailed reasons for your opinions, including the facts or assumptions that affect your reasoning and conclusions.

4. Preparation of Your Report

4.1. We would be grateful if you would set out the answers to the questions in a written report, having regard to the requirements set out in the Federal Court of Australia Expert Evidence Practice Note.

If you have any questions, please do not hesitate contact me [redacted].

Yours faithfully,

Brett Spiegel
Principal Lawyer
Phi Finney McDonald

Encl.

ANNEXURE A

Index to Brief

Tab No.	Date	Description of document(s) / category
A	**LETTERS OF INSTRUCTION**	
A2.	15 March 2023	Supplementary letter of instruction
B	**PLEADINGS**	
B4.	3 February 2023	Further Amended Statement of Claim
B5.	3 March 2023	Defence to Further Amended Statement of Claim

ANNEXURE B

Projected Torres Strait Impacts

8. Please explain how you would expect marine life in the Torres Strait to be impacted in the future if the global average surface temperature continues to increase beyond the Current Warming Level, by reference to the Torres Strait Impacts and any relevant Climate Impacts as defined in Annexure B to the Preliminary Letter of Instruction.

For the purpose of writing your report, and in answering both questions 7 and 8 of your instructions, please assume that the relevant Baseline is 1850-1900 (or 'pre-industrial levels' as adopted in the IPCC's Sixth Assessment Report).

ANNEXURE C

List of Figures

ANNEXURE D

CURRICULUM VITAE: TERENCE P. HUGHES

PERSONAL

Born in Dublin, Ireland
Citizenships: Australian, Irish

EDUCATION & DEGREES

Trinity College, Dublin: BA Mod., 1st Class in Zoology (1978),
Johns Hopkins University, Baltimore, USA: M.Sc. (1982), PhD (1984) in Ecology & Evolution
Universiti Malaysia Terengganu: Honorary D.Sc. (2014).
Trinity College, Dublin: Honorary D.Sc. (2019).
James Cook University, Australia: Honorary D.Sc. (2023).

PROFESSIONAL APPOINTMENTS

2021-	Emeritus Distinguished Professor, James Cook University
2005-2020	Inaugural Director, *ARC Centre of Excellence for Coral Reef Studies*
2009-2021	Distinguished Professor, James Cook University
2001-2005	Executive Scientific Director, *Centre for Coral Reef Biodiversity*, JCU
2000-2009	Professor (Personal Chair), James Cook University
1990-2000	Lecturer, Senior Lecturer, Associate Professor, JCU
1984-1990	NSF Post-doctoral Research Fellow, University of California, Santa Barbara

FELLOWSHIPS

2012-2017	Australian Research Council (ARC) Laureate Fellowship
2014	Einstein Professorship, Chinese Academy of Science
2007-2012	ARC Federation Fellowship
2006-	Fellow of the Beijer Institute for Ecological Economics, Swedish Academy
2003-2004	Visiting Professorial Fellow, University Perpignan, France
2002-2007	ARC Federation Fellowship
2001-	Elected Fellow of the *Australian Academy of Science*.

MAJOR GRANTS, AWARDS & PRIZES

2023	Suzanne Cory Medal, Australian Academy of Science
2014-2021	ARC Centre of Excellence grant ($30 million)
2020	BBVA Foundation, Frontiers in Knowledge Award, Spain
2020	Green Award, Bob Brown Foundation
2018-present	Clarivate Analytics, Highly Cited Researcher
2018	Climate Change Award, Prince Albert II, Monaco
2018	Sir John Maddox Prize "for standing up for science", London
2018	Huntsman Medal for Excellence in Marine Science, Royal Society of Canada

2008	The Darwin Medal, International Society for Reef Studies
2007	Australian Museum, *Eureka Sherman Prize for Environmental Science*
2005-2014	ARC Centre of Excellence grant ($22.5 million)
2004	*Silver Jubilee Award for Excellence*, Australian Marine Science Association
2003	Centenary Medal of Australia, for “services to Science”

RECENT PROFESSIONAL ACTIVITIES

	Member of AAAS, AMSA, ESA, ICRS, ACRS.
	Extensive field experience in Australia, Indonesia, Papua New Guinea, the Solomon Islands, Samoa, French Polynesia, Ireland and the Caribbean.
2023-2025	Member, Australian Research Council (ARC) College of Experts
2022-2023	Member, ARC Federation Fellowship Selection Advisory Committee
2020	Advisor to Ministry of the Environment, Japan
2019-	Advisory Board, *One Earth* (Cell Press)
2019	Ministerial appointee, peer-review of the 2019 Barrier Reef *Outlook Report* 2
2019	Parliamentary briefing on the Great Barrier Reef and climate change, Canberra
2018-	Inaugural Member, Ocean Solutions Initiative, Monaco
2015-	Member, Independent Expert Panel for the 2050 Reef Sustainability Plan
2018	Parliamentary briefing on IPCC Report and coral bleaching, Canberra
2018	Convener, *Coral Reef Futures Symposium*, Brisbane
2018	Working Group, *Governance of Coral Reefs*, Nice, France
2017-	Advisor to UNESCO on climate change
2015-2017	Leader, *Australian National Coral Bleaching Taskforce*
2014-2018	Board member, *Red Sea Research Centre*, KAUST, Saudi Arabia
2015-2016	Member, Queensland Great Barrier Reef Taskforce Review group
2015	Great Barrier Reef briefings, UNESCO, Paris and Berlin
2014	Witness, Australian Senate enquiry, Management of the Great Barrier Reef
2014	Ministerial appointee, peer-review of the 2014 Barrier Reef *Outlook Report*
2013-2015	*Ecology and Evolutionary Biology Committee*, Australian Academy of Science 2013
2013	Witness, Senate Enquiry, Amendment to the Great Barrier Reef Bill

RECENT PLENARY, SYMPOSIA & SEMINAR PRESENTATIONS

2023	Plenary Talk, ASLO Aquatic Sciences Meeting, Mallorca, Spain
2021	Annual Public Talk, 80th Anniversary, Dublin Institute for Advanced Studies
2020	Briefing to UNESCO World Heritage Centre, Paris
	Plenary Talk, Australian Coral Reef Society, AGM
	Plenary Talk, ARC Centre of Excellence for Coral Reef Studies, Australia
2019	Public talk, Trinity College Dublin
2019	Lecture tour in eastern USA (Columbia University, U. of Boston, U. of Maine, National Science Foundation, U. of Miami, FL State Uni, Nova University)
2019	Public Forum on Climate Change, National Maritime Museum, Sydney
2019	Annual Emeritus Faculty Lecture, Australian National University, Canberra
2019	Lecture tour in western USA (Scripps Institute, UCLA, UCSB, UCSC, Stanford, U. of Oregon, U. of Washington, Friday Harbor marine lab.).
2019	Guest Speaker, Al Gore’s *Climate Reality* Leadership Corps Training, Brisbane

2018 Keynote Speaker, Falling Walls Symposium, Berlin
Public Forum on Climate Change, Wentworth electorate, Sydney
Parliamentary Briefing on IPCC Report and Coral Bleaching, Canberra
Plenary Speaker, *Natural Disaster Symposium*, Australian Academy of Science
Ecological Society of America Symposium, New Orleans, USA
Distinguished speaker, Public Forum, Dalhousie University, Nova Scotia,
Huntsman Medal Plenary, Bedford Oceanographic Institute, Nova Scotia
Plenary Speaker, AMOS-ICSHMO Conference, Sydney
Panel Speaker, AMOS Public Forum on Climate Change, Sydney
Seminar, University of Barcelona, Spain
Seminar, University of Melbourne
Keynote Speaker, KAUST Symposium, Saudi Arabia

Editorial Experience: Advisory Board, *One Earth*, Cell Press (2019-); Managing Editor (1996-2000) and Biological Editor (1992-1996) of *Coral Reefs*, Springer; International Editor of *Israel Journal of Zoology* (2003-2006) and editorial board member for *Ecology & Society* (2004-2010).

Research Training: Hughes has supervised 16 Honours, 3 Masters, 39 PhD students, and 105 Postdoctoral Fellows.

PUBLICATIONS

Clarivate Analytics Highly Cited Researcher. Lifetime Google Scholar citations: >88,000. H-Index is 99.
http://scholar.google.com.au/citations?hl=en&user=MhJ2LfsAAAAJ&view_op=list_works&pagesize=100

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2. **Hughes, T.P.** 1983 Life histories and growth of corals over a depth gradient. Pages 17-20 in M. L. Reaka (Ed.) The Ecology of deep and shallow water coral reefs. Symposia Series for Undersea Research. NOAA, Rockville, MD.
3. **Hughes, T.P.** 1984. Population dynamics based on size rather than age: a general model with a reef coral example. *American Naturalist* 123: 778-795.
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16. **Hughes, T.P.**, D.J. Ayre and J.H. Connell 1992. The evolutionary ecology of corals. *Trends in Ecology and Evolution 7*: 292-295.
17. **Hughes, T. P.** 1993. Coral reef degradation: A long-term study of human and natural impacts. pp. 20-25, *In* R. N. Ginsburg, ed. *Global aspects of Coral Reefs*. University of Miami Press.
18. **Hughes, T. P**. 1993 (Editor). Disturbance: effects on coral reef dynamics. *Special Issue, Coral Reefs* 12(3&4): 115-233.
19. **Hughes, T. P.** 1994a. Catastrophes, phase-shifts, and large-scale degradation of a Caribbean coral reef. *Science* 265: 1547-1551. https://science.sciencemag.org/content/265/5178/1547 (Reprinted in *Environmental Management: Readings and Case Studies*. Ed. by L. Owens and T. Uniwin. (1997). Blackwell, Oxford, and in *Foundations of Ecological Resilience*. Ed by Lance H.
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22. **Hughes, T. P.** 1996. Demographic approaches to community dynamics: A coral reef example. *Ecology* 77(7): 2256-2260.
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Examples of Videos, Webinars, TV and Radio recordings

1. Breaking Boundaries: The Science of our Planet. Netflix documentary. https://www.netflix.com/au/title/81336476
2. Falling Walls, Berlin. *How Reef Management Can Secure Our Oceans for Future Generations*. https://www.youtube.com/watch?v=Lq6Sjb6pRzo
3. TEDx Talk: *Yes, we can save the world's coral reefs.* https://www.youtube.com/watch?v=x5LshSZn5RA
4. Darwin Medal Talk, 11th International Coral Reef Symposium: *Science, policy and the future of coral reefs*. http://www.nova.edu/ncri/11icrs/plenaries.html
5. Australian Academy of Science. *Anticipating ecological surprises: Managing reef resilience.* http://www.youtube.com/watch?v=dGEH8dTOut0&feature=youtube_gdata_player
6. National Climate Change Adaptation Research Facility. *Climate change and the future of coral reefs*. http://vimeo.com/25057831
7. ABC TV Future Forum: *Can coral reefs survive the 21st century* (60 minutes). https://www.abc.net.au/news/programs/future-forum/2011-08-01/can-coral-reefs-survive-the-21st-century/4121444
8. An 8-minute TV piece (ABC *Catalyst*) on the future response of the Great Barrier Reef to climate change: http://www.abc.net.au/catalyst/stories/3576802.htm