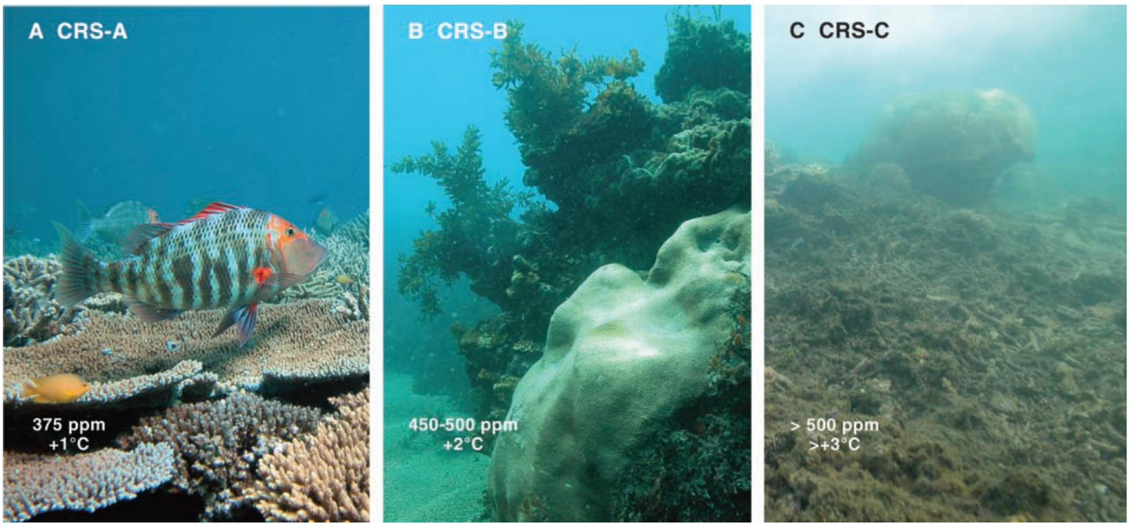
The current and future impacts of climate change and ocean acidification on the Great Barrier Reef



Report prepared for an objections hearing in the Land Court of Queensland regarding the proposed Carmichael Coal Mine

Reference numbers:
MRA428-14 & EPA429-14
MRA430-14 & EPA431-14
MRA432-14 & EPA433-14

Professor Ove Hoegh-Guldberg
Director, Global Change Institute
Australian Research Council Laureate Fellow
The University of Queensland

6 February 2015

Table of Contents

EXECUTIVE SUMMARY 3

INTRODUCTION 4

RELEVANT EXPERTISE 4

GREAT BARRIER REEF 5

THREATS TO THE LONG-TERM SUSTAINABILITY OF THE GREAT BARRIER REEF 5

CLIMATE CHANGE AND OCEAN ACIDIFICATION 7

IMPACTS AT CURRENT LEVELS OF CO_2 12

ASSUMPTIONS ABOUT FUTURE CLIMATE SCENARIOS 13

FUTURE CHANGES TO THE GREAT BARRIER REEF AS A RESULT OF CLIMATE CHANGE AND OCEAN ACIDIFICATION 14

CONTRIBUTION OF THE CARMICHAEL COAL MINE 19

DECLARATION 20

REFERENCES 21

APPENDIX 1: Curriculum vitae of Professor Ove Hoegh-Guldberg 25

EXECUTIVE SUMMARY

1. The Great Barrier Reef provides enormous benefits and income to the Australian people ($5-6 billion pa from tourism and fisheries). It is highly valued by the world's people, having been World-Heritage listed in 1981 and being widely recognised as one of the most pristine and valuable coral reefs in the world. It is threatened by both local (e.g. declining coastal water quality) and global factors (climate change and ocean acidification due to burning of fossil fuels), with the latter being widely recognised as the greatest threat to the health of the Great Barrier Reef. The rate at which ocean temperature and pH are changing is unprecedented in 65 million years if not 300 million years, and is having a direct impact on the health of the Great Barrier Reef and its organisms and ecosystems by driving unprecedented mass coral bleaching and mortality events, and causing calcification rates to decline in response to declining carbonate ion concentrations.

2. The Australian Government's lead agency for the protection of the Great Barrier Reef, the Great Barrier Reef Marine Park Authority (GBRMPA), recently found that climate change remains the most serious long-term risk facing the Reef and is likely to have far reaching consequences for the Region's environment. The GBRMPA also found that at present, global emissions are not on track to achieve the agreed global goal of limiting global temperature rises to beneath 2°C and even a 2°C rise would be a very dangerous level of warming for coral reef ecosystems, including the Great Barrier Reef, and the people who derive benefits from them. The GBRMPA found that to ensure the Reef remains a coral-dominated system, the latest science indicates global average temperature rise would have to be limited to 1.2°C. These conclusions are consistent with the latest available science and the most recent assessment report of the Intergovernmental Panel on Climate Change (IPCC; AR5).

3. The addition of further carbon dioxide to the atmosphere by enterprises such as the Carmichael mine will directly damage the Great Barrier Reef and reduce its ecological services, and hence the income and livelihoods of people both here in Australia and overseas. Conservative projections of climate change reveal that coral reefs like the Great Barrier Reef will be fundamentally changed into non-coral dominated ecosystem if atmospheric carbon dioxide continues to increase at its current rate. Coal mining operations such as the Carmichael mine will result in very significant impacts on Australian people and industries such as fishing and tourism. These impacts will also be felt on coral reefs, people and industries around the globe.

INTRODUCTION

4. I have been asked by Land Services of Coast and Country Inc. (LSCC) to provide an expert opinion of the likely ecological impacts of climate change and ocean acidification on the Great Barrier Reef, Australia.

5. This report has been prepared in response to that request for use in an objection hearing in the Land Court of Queensland concerning a large open-cut coal mine, the Carmichael Coal Mine, an open-cut and underground coal mine proposed to be located 160km north-west of Clermont in the Galilee Basin of central Queensland (the mine). The mining lease term applied for is 30 years; however, the expected life of the mine is 60 years.

6. The coal from the mine is proposed to be crushed, processed and blended on site before being transported by rail to the Port of Abbot Point for export to India. If it proceeds, the mine will produce thermal coal that is intended to be sold to other companies in the Adani Group to be burnt in coal-fired power stations in India to generate electricity.

7. The expected direct and indirect greenhouse gas emissions from the mining, transport and burning of the coal from the mine are 4.729 gigatonnes of carbon dioxide (Gt CO_2) according to the Joint Expert Report on Climate Change – Emissions prepared by Dr Malte Meinshausen and Dr Chris Taylor, dated 22 December 2014.

8. For the purposes of preparing this report, in addition to the Joint Expert Report on Climate Change – Emissions, I have been provided with a copy of the objection lodged by LSCC to the coal mine proposed by the applicant the subject of the appeal. I am instructed that the environmental impact statement prepared for the mine does not contain any analysis of the impacts of climate change or ocean acidification on the Great Barrier Reef (or any other ecosystem).

RELEVANT EXPERTISE

9. I am a Professor of Marine Studies and the Director of the Global Change Institute at The University of Queensland and Deputy Director of the Australian Research Council (ARC) Centre for Excellence for Reef Studies. I am also a Fellow of the Australian Academy of Science, as well is holding a prestigious Australian Research Council Laureate Fellowship. My fields of research and professional interest include:

   (a) coral reefs and marine studies;

   (b) the effects of climate change (particularly ocean warming and acidification) on reef-building corals, tropical coral reefs and related marine ecosystems;

   (c) coral bleaching and mortality, and their connection to global warming and ocean acidification;

   (d) biology of symbiotic associations in reef-building corals and the impacts of stresses such as global warming upon these associations.

10. Appendix 1 to this report provides a copy of my resume.

11. In preparing my report I understand my duty as an expert witness before the Court based on rule 24C of the *Land Court Rules 2000* is to assist the Court. While I appear pro bono to assist the Court in these proceedings, I note also that my duty to assist the Court would override any obligation I may have to any party to the proceeding or to any person who is liable for my fees or expenses.

GREAT BARRIER REEF

12. The Great Barrier Reef is one of the world's largest and most spectacular coral reef ecosystems. Lining almost 2,100 km of the Australian coastline, the Great Barrier Reef is the largest continuous coral reef ecosystem in the world. It is home to an amazing variety of marine organisms including 6 species of marine turtles, 24 species of seabirds, over 30 species of marine mammals, 350 coral species, 4,000 species of molluscs and 1,500 fish species. The total number of species number into the hundreds of thousands. New species are described each year, and some estimates suggest we are familiar with less than 50% of the total number of species that live within this amazing ecosystem. The intergenerational benefits from the sustainable management of Great Barrier Reef are enormous.

13. The Great Barrier Reef is also considered to be one of the most pristine ecosystems, which is a consequence of a relatively low human population pressure (as compared to other regions like Indonesia where tens of millions of people live directly adjacent to coral reefs) and a modern and well-resourced management agency, the Great Barrier Reef Marine Park Authority (GBRMPA), which practices state-of-the-art, science-based environmental management. The Great Barrier Reef Marine Park was established in 1975 by the Federal Government and was proclaimed a World Heritage Area in 1981 (Figure 1).

14. The Great Barrier Reef provides enormous economic value to Queensland through its fisheries and tourism industries. Estimates of its value range between $5-6 billion each year, with $5.2 billion in value added and about 64,000 FTEs generated by the tourism sector (Deloitte Access Economics, 2013). Fisheries associated with the Great Barrier Reef earn $193 million each year (ibid). These industries are largely sustainable, and represent annual contributions to the Queensland and Australian economies *ad infinitum*.

THREATS TO THE LONG-TERM SUSTAINABILITY OF THE GREAT BARRIER REEF

15. Coral reefs like the Great Barrier Reef are threatened by both local (e.g. water quality, coastal degradation, pollution and fishing pressure) and global (e.g. global warming, ocean acidification) stressors. These two categories of stress are distinguished in terms of whether particular stresses acting on a coral reef arise from 'local' sources such as a fishing industry or coastal land-use, or from global sources which arise from changes to the Earth's atmosphere and climate. Both local and global factors have already had major impacts on coral reefs. For example, the over-exploitation of coral reef species in many countries has led to the major decline in key fish species on coral reefs (e.g. herbivorous fish) which have led in turn to major changes in the ecological structure of coral reefs (Jackson et al. 2001). The major decline of reef-building corals on Caribbean reefs over the past 40 years (from >60% of the reefs covered in corals in 1970 to less than 10% coral cover

today; Hughes 1995) has been mainly attributed to the removal of herbivorous fish and the input of waste nutrients by over-populated coastal regions.

16. While overexploitation has affected some parts of the Great Barrier Reef, there is a general perception that the main threats to the Great Barrier Reef stem more from reduced water quality (i.e. increased nutrients and sediments) as a result of agricultural activities and deforestation in coastal Queensland as opposed to the fishing of herbivorous species at unsustainable levels (which does not occur to any real extent). Agricultural activities have resulted in a tenfold increase in the flux of sediments (and probably nutrients) down the rivers of Queensland starting soon after the arrival of European farmers, hard-hoofed cattle and coastal agriculture (McCulloch et al. 2003). The increased nutrient and sediment levels flowing out of these disturbed river catchments and coastal areas in Queensland is most likely to have driven some of the loss of inshore Great Barrier Reef coral reefs (i.e. first 1–5 km of coastal reef system).

Figure 1 Map of the Great Barrier Reef Marine Park (courtesy of GBRMPA)

CLIMATE CHANGE AND OCEAN ACIDIFICATION

17. Human driven changes to the greenhouse gas content of the atmosphere (principally carbon dioxide (CO_2) and methane) have driven changes to the average temperature of the planet (see pages 4-6 of the Joint Report by Taylor and Meinshausen). Over 90% of the extra heat trapped by the enhanced greenhouse effect has been absorbed by the oceans. These changes have resulted in rising ocean heat content and increases in the temperature of the upper layers of the ocean (IPCC 2007; 2014). Sea surface temperature of the global ocean has increased by about 0.5^{o}C during the 20th century. The global average warming over the past 50 years is about 0.1^{o}C per decade in the surface and decreases to 0.017^{o}C per decade at 700 m (Levitus et al., 2009). Changes are greatest in the northern hemisphere and at high latitudes (Levitus et al., 2009). As a result, the Great Barrier Reef waters are 0.4°C warmer than they were 30 years ago (Lough 2007).

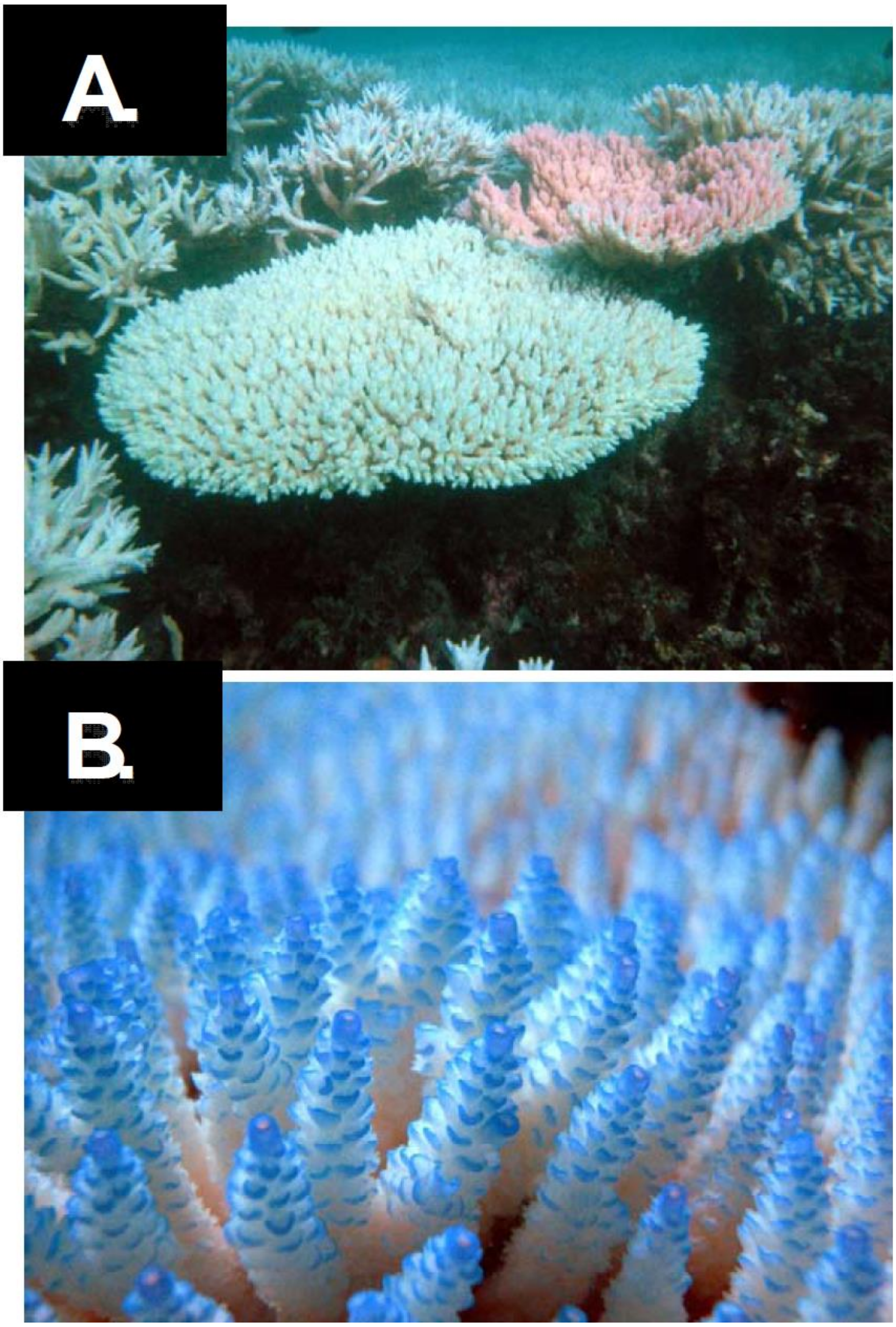
18. A large portion of carbon dioxide that is emitted into the atmosphere by burning fossil fuels is absorbed into the oceans (approximately 30%) and reacts with seawater to produce more acidic conditions, a process known as “ocean acidification” (Figure 4). This process is commonly unrecognised in public discussions about climate change and has been called “the evil twin” of climate change (Pelejero et al. 2010). Although it will be hard to quantify the effects separately, and indeed their synergistic behaviour, evidence gathered over the last years suggests that ocean acidification could represent an equal (or perhaps even greater) threat to the biology of our planet (Pelejero et al. 2010). Increasing atmospheric carbon dioxide from past human activities has also resulted in 0.1 pH decrease (i.e. the ocean has become more acidic) which has removed 30–40 μmol kg^{-1} carbonate ions from ocean bodies like the Coral Sea that normally contain between 250–300 μmol kg^{-1} (Hoegh-Guldberg et al 2007; IPCC 2013). As carbonate ions form the substrate for calcification, the decrease in carbonate ions impacts the ability of many marine organisms to form their skeletons which is ultimately crucial to the construction and maintenance of coral reefs (Kroeker et al. 2013; Hendriks et al. 2009; Kleypas and Langdon 2006; Kleypas et al. 2006; Raven et al. 2005).

19. In addition to the size of the absolute change from climate change and ocean acidification, global conditions have varied at unprecedented rates of change. Changes in atmospheric carbon dioxide (hence carbonate ion concentrations in the oceans) and sea temperature has increased at rates that are 2–3 orders of magnitude faster than the majority of changes that have occurred over the past 420,000 years at least (see Table 1 in Hoegh-Guldberg et al. 2007). The latest Intergovernmental Panel on Climate Change (IPCC) assessment report (AR5) has extended this analysis and has concluded via consensus that the current rate of change in pH and associated variables is the highest in 65 million years, if not 300 million years (IPCC 2014).

20. These changes in the conditions surrounding coral reefs have already had major impacts on coral reefs. Short periods of warm sea temperatures, once probably harmless but now riding on top of higher sea temperatures due to climate change, have pushed corals and their dinoflagellate symbionts above their thermal tolerance. This has resulted in episodes of mass coral bleaching that have increased in frequency and intensity since they were first reported in the scientific literature in

1979 (see reviews by Brown 1997, Hoegh-Guldberg 1999, Hoegh-Guldberg et al. 2007; Baker et al. 2008). Coral bleaching (Figure 2) occurs when the symbiosis between corals and their critically important dinoflagellate symbionts breaks down. These symbionts provide most of the energy needs of the coral host. The breakdown of the symbiosis can occur for a number of reasons, the major one of which is heat stress. The result of the breakdown of the symbiosis is that the brown dinoflagellate symbionts leave the otherwise translucent coral tissue, leaving corals to remain as a stark white colour (hence the term 'bleached'). Without their energy source, bleached corals are susceptible to starvation, disease and death.

Figure 2 **A. Coral reef after experiencing mass coral bleaching (Great Keppel Island, southern Great Barrier Reef). B. Close-up of bleached coral showing intact but translucent tissues over the white skeleton. Photos by O. Hoegh-Guldberg, January 2006.**

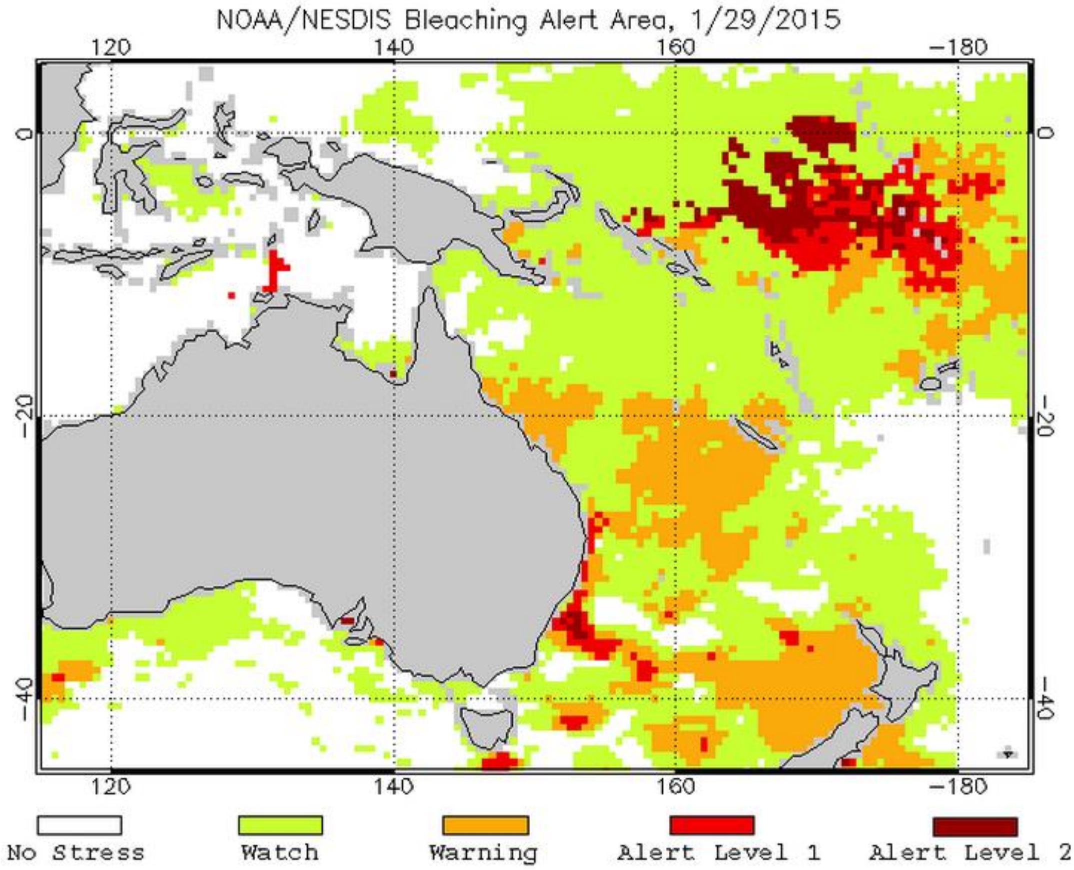


21. In 1998, most coral reefs worldwide experienced mass coral bleaching over a 12 month period that began in the eastern Pacific in December 1997. While many coral reef communities recovered from the subsequent 12 month period of extremely warm sea temperatures (driven by an unusually strong El Niño disturbance on top of the steadily rising sea temperatures globally), many coral reefs such as those in the Western Indian Ocean, Okinawa, Palau and Northwest Australia were devastated by the mass mortality which followed these bleaching events. In these cases, coral bleaching was followed by mass mortalities that removed over 90% of the resident corals on these reef systems. At the end of the 12 month period, bleaching across the globe had removed an estimated 16% of the world's coral (Hoegh-Guldberg 1999). Whereas some of these reefs have begun to recover, recovery has been exceedingly slow and coral cover on many of these reefs does not resemble that seen prior to 1998 (Wilkerson 2004).

22. The Great Barrier Reef has been affected by coral bleaching as a result of heat stress six times over the past 25 years. Recent episodes (i.e. 1998, 2002) on the Great Barrier Reef have been the most intense and widespread. In 1998, the Great Barrier Reef experienced what was considered at the time as its worst case of mass coral bleaching. In this event over 50% of the coral reefs within the Great Barrier Reef Marine Park were affected. This was followed, however, by an even larger event in 2002 which affected over 60% of the reefs with the Great Barrier Reef Marine Park. Fortunately in both cases, only 5–10% of corals affected by coral bleaching died, which was far less than the mortalities seen in regions such as the Western Indian Ocean, Okinawa or Northwest Australia (ranging up to 46%; Hoegh-Guldberg 1999). The latter was primarily because conditions on the Great Barrier Reef did not get as hot for as long as that seen in Western Indian Ocean or Northwest Australia. It is significant that climate change is now recognised as 'the greatest long-term threat to the Great Barrier Reef' (GBRMPA 2014: 5-5).

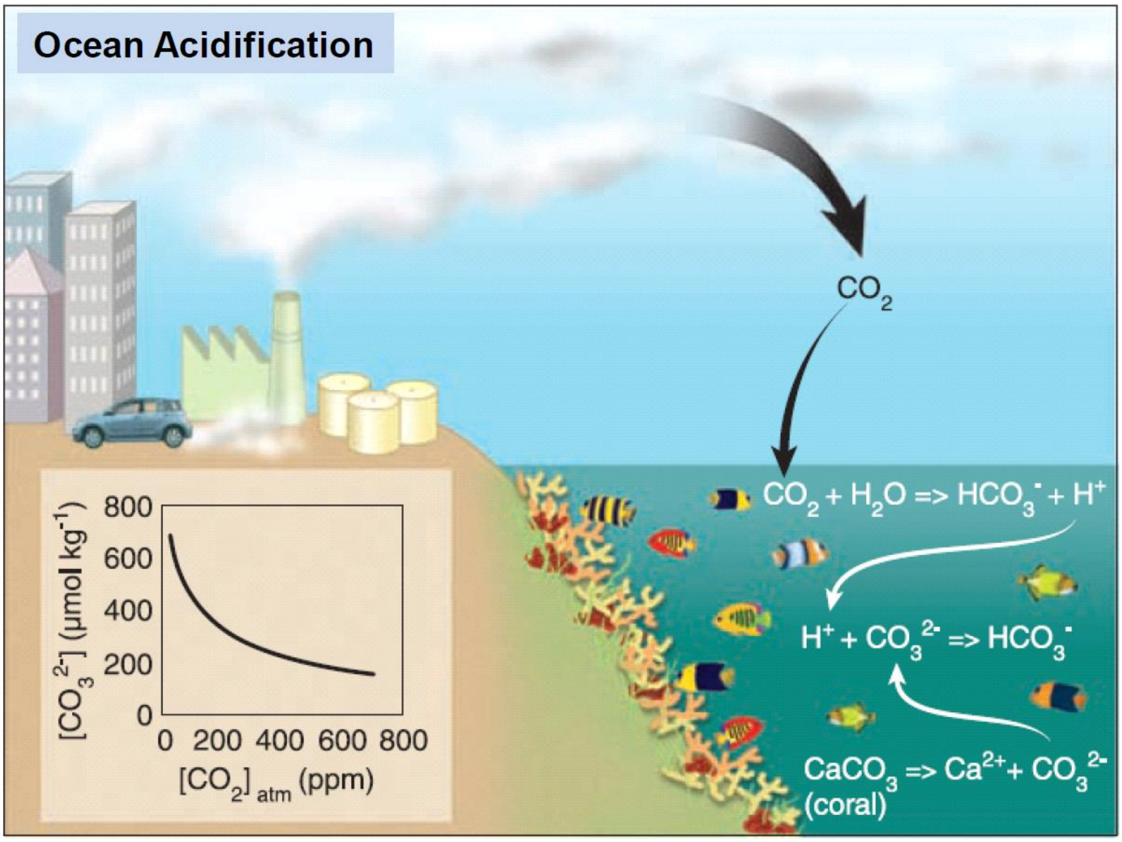
23. Sea temperatures in early 2015 have begun to approach the thermal threshold above which mass coral bleaching and mortality will occur. Over the past months, the temperature of water bathing the Great Barrier Reef has been steadily approaching the temperatures (at which mass coral bleaching and mortality is likely to occur). In the Figure 3 below from NOAA in Washington DC (http://coralreefwatch.noaa.gov/satellite/baa.php), bleaching has been reported from areas that are red in colour. Areas that are green and orange are areas in which temperatures are just below the bleaching threshold - but are considered to be under "watch" and "warning" levels. The risk of bleaching will continue to grow in these areas over the next two months unless cyclonic conditions develop, which would otherwise cool water due to increased mixing by the storm conditions. While these levels of natural variability might not have caused mass coral bleaching and mortality in the past, the increase in the background temperature of the ocean has meant that these small upward increases in sea temperature now drive an increasing frequency and intensity of mass coral bleaching and mortality are.

Figure 3 **NOAA/NESDIS bleaching alert area as at 29 January 2015**



24. The changes to water chemistry arising from ocean acidification, are adding additional pressure on coral reefs. As noted above, increasing concentrations of atmospheric carbon dioxide due to burning fossil fuels result in large quantities (approximately 30%) of additional carbon dioxide entering the ocean. Once in the ocean, carbon dioxide combines with water to produce a weak acid, carbonic acid, which subsequently converts carbonate ions into bicarbonate ions. This leads to a decrease in the concentration of carbonate ions, which ultimately limits the rate of marine calcification (Figure 4). A recent study has found a 14.5% decrease in the calcification rate of 328 long-lived corals on the Great Barrier Reef since 1990, which was unprecedented in the 400 years of record examined and appears to be a direct result of the changing temperature and sea water chemistry (De'ath et al. 2009). These long calcification records are possible because corals lay down distinct annual layers of calcium carbonate (much like tree rings), which in the case of long-lived corals, can lead to precise measures of yearly calcification going back hundreds of years.

Figure 4 **Schematic diagram showing the link between atmospheric carbon dioxide, ocean acidity and the calcification rates of coral reefs and other ecosystems. Insert diagram depicts relationship between atmospheric carbon dioxide (CO_2 atm) and ocean carbonate concentrations. (Reprinted courtesy of Science Magazine)**



25. While we are just starting to understand the impacts of ocean acidification on the Great Barrier Reef, there is consensus that the rate of change in the acidity of the ocean poses as great a threat to coral reefs as does global warming (Raven et al. 2005; Hoegh-Guldberg et al. 2007). This concern is heightened by the fact that current levels of ocean acidification may already lie outside those experience for the last million years at least (Pelejero et al. 2010). It is also important to note that ocean acidification and elevated temperature can also act synergistically making the effect of each factor more significant when they occur together, with thermal tolerance of reef-building corals to temperature being reduced when they are also exposed to ocean acidification at the same time (Anthony et al. 2008).

26. The combined pressure of local (i.e. deteriorating water quality) and global (ocean warming and acidification) have led to the loss of 50% of the corals on the Great Barrier Reef since the early 1980s (De'ath et al. 2012). In addition to increasing impacts from warmer than normal ocean temperatures (leading to mass coral bleaching and mortality) changing conditions have led to a reduced resilience of coral reefs to disturbances such as Crown of Thorns starfish (increasing due to added nutrients) and cyclone impacts.

IMPACTS AT CURRENT LEVELS OF CO_2

27. Prior to the beginning of the Industrial revolution, atmospheric concentrations of carbon dioxide (CO_2) were around 280 parts per million (ppm) (IPCC 2007). These concentrations have risen to approximately 400 parts per million (ppm) at present based on observations at the Mauna Loa observatory in Hawaii after season fluctuations are accounted for (NOAA 2015). Current rates of emissions of CO_2 from human activities are causing atmospheric CO_2 concentrations to rise by approximately 2 ppm per year (IPCC 2007, 2013). This rate of increase in atmospheric carbon dioxide is largely unprecedented. Even during the highest rates of change seen during the rapid transition out of the last ice age, the same amount of change we are currently experiencing in a single year occurred over 100-200 years. This transition was accompanied by massive changes to the Earth’s climate and biosphere.

28. Temperature-induced mass coral bleaching began impacting coral reefs on a wide geographic scale in the early 1980s. Given that there is a lag time between the achievement of a certain level of atmospheric CO_2 and the resultant warming (conservatively estimated here as 10-20 years), impacts on coral reefs began atmospheric CO_2 levels approached ~320 ppm. When CO_2 levels reached ~340 ppm, sporadic but highly destructive mass bleaching occurred in most reefs world-wide, often associated with El Niño events. Recovery was dependent on the vulnerability of individual reef areas and on the reef’s previous history and resilience. At today’s level of ~400 ppm, allowing a lag-time of 10 years for sea temperatures to respond, most reefs world-wide are committed to an irreversible decline (Veron et al. 2009). The rate, extent and nature of this decline will become increasingly severe if atmospheric CO_2 concentrations continue to increase above current levels. Returning the atmosphere to a safe level of CO_2 for coral reefs requires atmospheric CO_2 concentrations of <350 ppm (Veron et al. 2009).

29. The GBRMPA found that optimum limits for coral reef ecosystems of atmospheric CO_2 are at or below 350 ppm (GBRMPA 2014: 5-5). It found further that there is already evidence of effects on the Reef at present levels of 400 ppm CO_2, such as declining calcification rates, that are suggested to be caused by temperature stress and ocean acidification and atmospheric concentrations of CO_2 above 450 ppm pose an extreme risk for coral reef ecosystems and tropical coastal habitats (GBRMPA 2014: 5-5).

30. This information suggests that the current 2°C guardrail may be too high for the majority of coral reefs (Donner et al. 2005; Veron et al 2009; Frieler et al 2012). Many reef users with long-term and extensive experience (e.g. Anthony Wayne Fontes; Lay Witness Statement) report that “many people that have visited the reef in the past, perhaps 10 years ago, when they returned they are actually shocked at the reduction in reef quality they see today.”

31. Given the growing evidence that relatively small increases in the concentrations of atmospheric carbon dioxide will trigger a wide array of irreversible changes to critically important marine ecosystems, avoiding any further increases and aiming to reduce the atmospheric concentration of CO_2 below 350 ppm in the long term is seen by many experts as an international imperative (Veron et al 2009; Hoegh-Guldberg and Bruno 2010; Frieler et al 2012; IPCC 2014). Reducing the

atmospheric concentration of CO_2 to below 350 ppm is critical for preserving a safe climate system (Hansen et al. 2008, Rockström et al. 2009). Not pursuing this objective will escalate growing losses from a range of failing ecosystems and agriculture, increasing numbers of extreme events, and other health and societal impacts.

ASSUMPTIONS ABOUT FUTURE CLIMATE SCENARIOS

32. While current levels of atmospheric CO_2 are already detrimental for the Great Barrier Reef and other coral reefs globally, their continued existence in anything resembling their current form largely dependent upon the level at which atmospheric CO_2 is stabilised (Hoegh-Guldberg et al. 2007). It is important to realise that concentrations of greenhouse gases such as CO_2 above certain levels will mean that stabilisation of conditions, including those in the ocean, will not occur for hundreds if not thousands of years (IPCC 2013). This is likely to be highly disruptive to natural as well is human systems (IPCC 2015).

33. To project future increases in ocean warning and acidity requires assumptions to be made about future emissions of CO_2 and other greenhouse gases. It is unnecessary for the purposes of this report to make assumptions about the policies or technologies that must be employed to achieve emission reductions. It is sufficient for this report to discuss the physical consequences for the Great Barrier Reef if atmospheric CO_2 are stabilised or not at different atmospheric concentrations. The means by which stabilisation is achieved are policy matters that are unnecessary to consider for the purposes of this report. For the purposes of this report the following three basic scenarios are discussed based on the analysis in Hoegh-Guldberg et al. (2007) and Hoegh-Guldberg and Hoegh-Guldberg (2008):

Scenario	**Assumptions**
CRS-A	Atmospheric CO_2 is stabilised close to current levels of 390 ppm or up to approximately 420 ppm. Mean global temperature rises above pre-Industrial levels of approximately 1 – 1.5°C occur.
CRS-B	Atmospheric CO_2 is stabilised between 450 and 500 ppm. Mean global temperature rises above pre-Industrial values of approximately 2–2.5°C occur.
CRS-C	Atmospheric CO_2 is either not stabilised or is stabilised above 500 ppm at very long time horizons. Mean global temperature increase in above pre-Industrial levels of 2.5°C occur.

FUTURE CHANGES TO THE GREAT BARRIER REEF AS A RESULT OF CLIMATE CHANGE AND OCEAN ACIDIFICATION

34. Climate change and ocean acidification are placing coral reefs in conditions that they have not experienced over the past 740,000 years, if not 20 million years (Raven et al 2005; Hoegh-Guldberg et al 2007; Pelejero et al. 2010). Even the relatively rapid changes during the ice age transitions, which resulted in major changes in the biota of the planet, occurred at rates of change in CO_2 and temperature which were at least two orders of magnitude (i.e. one hundred times) slower than the rate of change that has occurred over the past 150 years. According to the latest IPCC report, there is scientific evidence that these changes are occurring at rates which dwarf even the most rapid changes seen over the past 65 if not 300 million years (IPCC 2014). Most evidence suggests that this rate of change will increase and already exceeds the biological capacity of coral reefs to respond via genetic change (evolution). As a result, there is a high degree of consensus within scientific circles that coral reefs, like a large number of other ecosystems, are set to undergo transformative and rapid changes over the coming decades (IPCC 2007, Done et al. 2003, Donner et al. 2005; IPCC 2014).

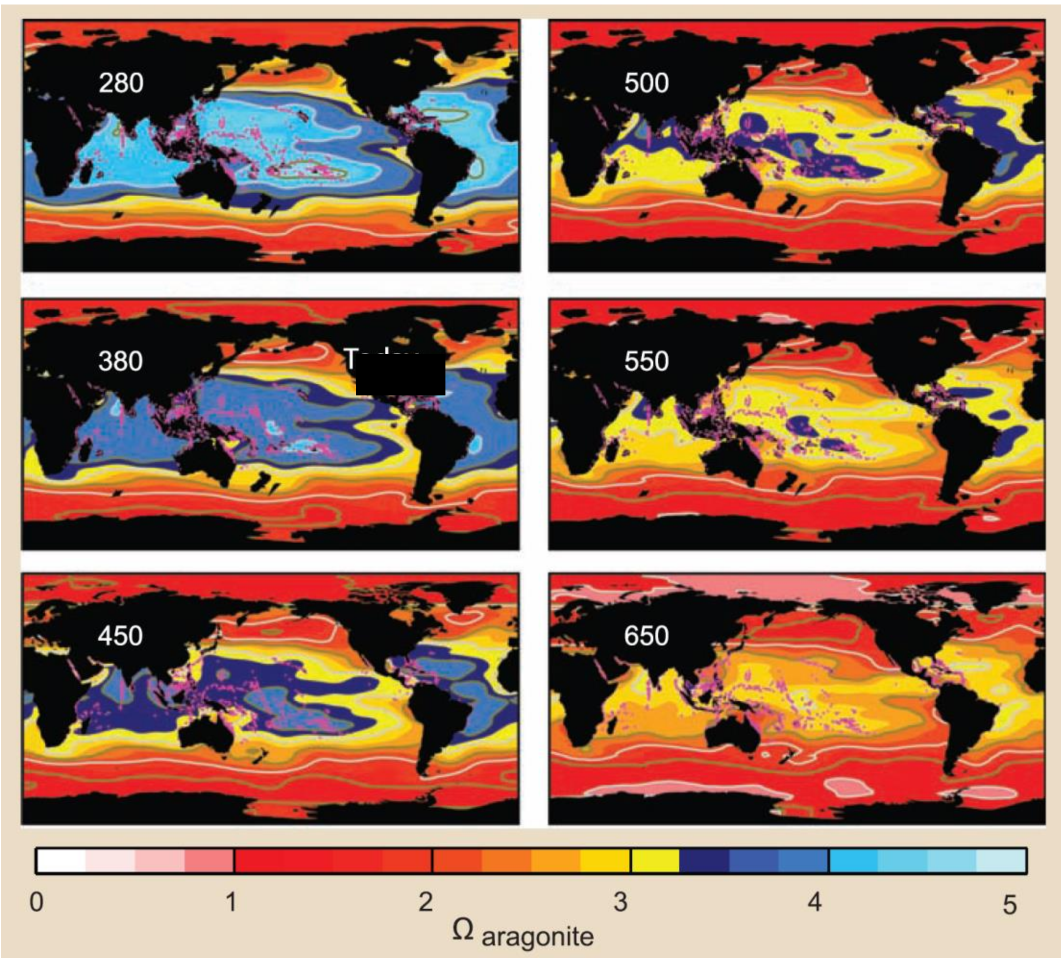
35. Consideration has recently been given to how reef systems like the Great Barrier Reef will change in response to changes in atmospheric gas composition. It is accepted that the environmental values of the Great Barrier Reef will continue to decline as average global temperature increase (page 5, Joint Report, Taylor and Meinshausen). In this regard, Hoegh-Guldberg et al. (2007) concluded that carbonate coral reefs such as the Great Barrier Reef are unlikely to maintain themselves beyond atmospheric carbon dioxide concentrations of 450 ppm. The evidence came from a wide array including field, laboratory and other sources. Neither temperature (+2°C above pre-industrial global temperatures) nor ocean carbonate concentration (<200 μmol kg^{-1}, which arise when $CO_{2\ atm}$ reaches approximately 450 ppm) in these scenarios are suitable for coral growth and survival, or the maintenance of calcium carbonate reef structures. These conclusions are based on the observation of how coral reefs behave today and how they have responded to the relatively mild changes in ocean temperature so far. Mass coral bleaching, for example, is triggered at temperatures that are 1°C above the long-term summer maxima which is the basis for highly successful satellite detection programs (Strong et al. 2004). Coral reefs also do not accrete calcium carbonate or form limestone-like coral reefs in water that has less than 200 μmol kg^{-1} carbonate ion concentrations (roughly equivalent to an aragonite saturation of 3.25; Kleypas et al. 1999). These conditions will dominate tropical oceans if carbon dioxide concentrations exceed 450 ppm (Figure 5).

36. Taking the two drivers together allows the scientific community to project how conditions on the Great Barrier Reef will change if atmospheric concentrations of carbon dioxide continue to increase. The critical point for carbonate coral reef systems like the Great Barrier Reef arises when carbon dioxide concentrations exceed 450 ppm. At this point, the majority of evidence points to tropical reef systems that do not have the dominant coral populations. As coral reefs are the results of vibrant coral communities, many of the services (e.g. fisheries, tourist use) are severely degraded at this point.

37. Using the evidence and conclusions of the Hoegh-Guldberg et al. (2007) study, in turn based on previous studies (Hoegh-Guldberg 1999, Donner et al. 2003, Hoegh-Guldberg and Hoegh-Guldberg 2003), three basic scenarios for the Great Barrier Reef can be assigned (Figure 6).

38. It is important that the three scenarios in Figure 6 be seen as representing a continuum of change and not a set of discrete thresholds or 'tipping points'. That said, it is also noteworthy that coral reefs regularly show non-linear behaviour (i.e. minimal change for a period and then a sudden and catastrophic decline in once-dominant species as an environmental variable changes, as described by Hughes (1995) and, hence, while we don't know where these 'breakpoints' exist relative to particular concentrations of atmospheric carbon dioxide, it is crucial to understand that there is a significant likelihood that ecosystems like the Great Barrier Reef might experience phase-transitions such as those already seen in the Caribbean and other coral reef realms (Hughes 1995).

Figure 5 **Calculated values for aragonite saturation, which is a measure of the ease with which calcium carbonate crystals (aragonite) form, as a function of geography. Coral reefs today only form where the aragonite saturation exceeds 3.25, which is illustrated by the blue coloured areas (coral reefs found today are indicated in this panel by the pink dots). As the concentration of carbon dioxide in the atmosphere increases from 390 ppm today, the extent of conditions that are suitable for the formation of carbon coral reefs dwindles until there are few areas with these conditions left at 550 ppm and above. Ocean acidification represents a serious threat to carbonate reef systems and may see the loss and decay of reef structures across the entire tropical region of the world (Reprinted courtesy of Science Magazine; Hoegh-Guldberg et al. 2007).**



39. In the case of minimal climate change (scenario CRS-A) atmospheric carbon dioxide stabilises at around current levels or up to 420 ppm, conditions surrounding the Great Barrier Reef will largely resemble those of today with the following important differences.

40. Firstly, mass coral bleaching events are likely to be more frequent and intense relative to those that have occurred over the past 25 years. Based on modelling studies (Hoegh-Guldberg 1999, Done et al. 2002, Donner et al 2003; IPCC 2014), mass coral bleaching events are likely to be twice as frequent as they are today if sea temperatures surrounding the Great Barrier Reef increased by another 0.55°C over and above today's temperatures. Changes in the sea temperature of this magnitude will also increase the intensity of the thermal anomalies which, depending on the particular phase of the El Niño Southern Oscillation and longer term changes in sea temperature such as the Pacific Decadal Oscillation (PDO), will result in large scale impacts on coral reefs like the Great Barrier Reef. This will result in a greater likelihood of mass mortalities among coral communities, and an overall downward adjustment of average coral cover on coral reefs like those in the Great Barrier Reef Marine Park (Hoegh-Guldberg et al. 2007). Some areas may lose coral permanently while others, such as those in well flushed and ecologically resilient locations (e.g. with good water quality, intact fish populations), are likely to remain coral dominated.

41. Secondly, there is likely to be a shift towards more degraded the three-dimensional reef frameworks as concentrations of carbonate ions decrease and become limiting for the calcifying activities of corals. The same time, organisms that dissolved and remove calcium carbonate appear to be stimulated (Dove et al. 2013). This may remove the habitat for some species (e.g. coral-dwelling fish and invertebrate species) while it may increase habitat for others (e.g. some herbivorous fish species). It is important to appreciate that reefs are likely to be populated by some form of marine life. Equally importantly, however, the replacement organisms (possibly seaweeds and cyanobacterial films) are unlikely to match (replace) the beautiful and charismatic coral reefs that we currently enjoy.

42. The importance of marine parks in protecting and maintaining conditions for coral reefs would be heightened as impacts from climate change and ocean acidification increase. Several studies have shown that the recovery of coral reefs (and hence their long-term sustainability) after climate change disturbances such as coral bleaching and mortality events is faster if the affected reefs are protected from local stresses like poor water quality and over exploitation of herbivorous fish (Hughes et al. 2003, Hughes et al. 2007).

43. If atmospheric CO_2 increases beyond 450 ppm, large-scale changes to coral reefs would be inevitable. Under these conditions, reef-building corals would be unable to keep pace with the rate of physical and biological erosion, and competition with other organisms, and coral reefs would slowly shift towards non-carbonate reef ecosystems. As with non-carbonate reef systems today, primary productivity and biodiversity would be lower on these transformed systems. Reef ecosystems at this point would resemble a mixed assemblage of fleshy seaweed, soft corals and other non-calcifying organisms, with reef-building corals being much less abundant (even rare). As a result, the three-dimensional structure of coral reefs would begin to crumble and disappear. Depending on the influence of other factors such as the

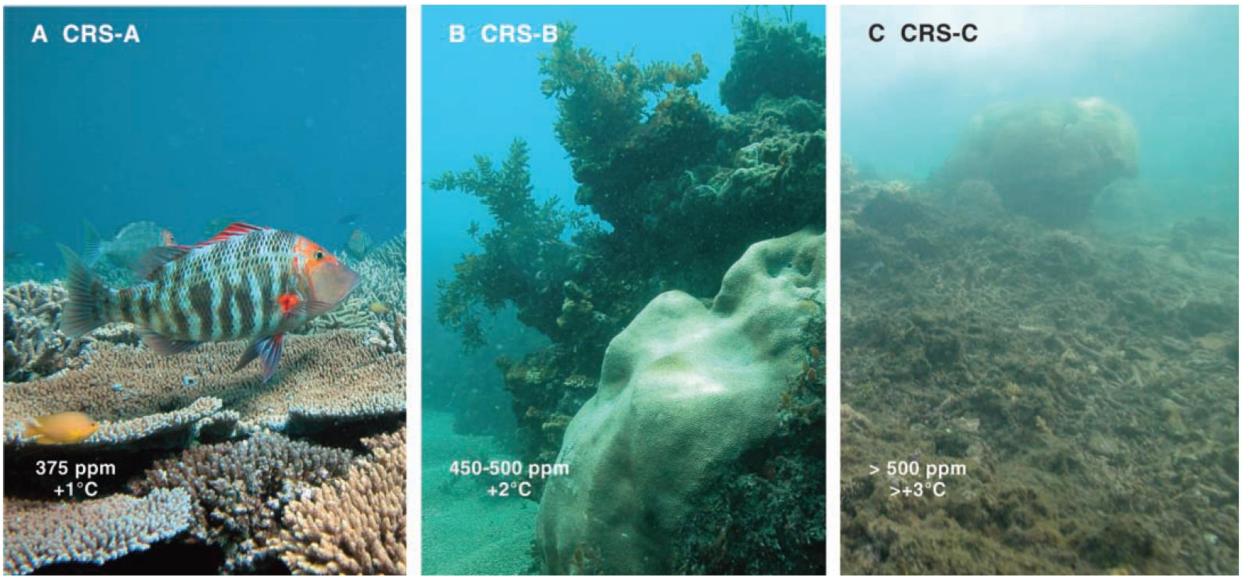
intensity of storms, this process may happen at either slow or rapid rates. It is significant to note that this has happened relatively quickly (over of an estimated 30 to 50 years) on some inshore sites on the Great Barrier Reef.

44. The loss of the three-dimensional structure has significant implications for other coral reef dwelling species such as populations where at least 50% of the fish species are likely to disappear with the loss of the reef-building corals and the calcium carbonate framework of coral reefs (Munday et al. 2007). Loss of the calcium carbonate framework would also have implications for the protection provided by coral reefs to other ecosystems (e.g. mangroves and sea grasses) and human infrastructure, as well as industries such as tourism which depends on highly biologically diverse and beautiful ecosystems. While coral reefs under this scenario would retain considerable biodiversity, their appearance would be vastly different to the coral reefs that attract tourists today (Figure 6B).

45. The rapid reduction in coral cover will have major consequences for other organisms and reef services and functions. Many organisms that are coral dependent will become rare and may become locally or globally extinct (Carpenter et al. 2008). Other organisms, such as herbivores, may actually increase as reefs change from coral domination to domination by algal/cyanobacterial organisms. Increases in the abundance of cyanobacteria may have implications for the incidence of poisoning by the toxin ciguatera, a major problem in some areas of the world already (Llewellyn 2010).

46. If the concentration of CO_2 in the atmosphere exceeds 500 ppm and conditions approach those of CRS-C, conditions will exceed those required for the majority of coral reefs across the planet (Figure 6C). Under these conditions, the three-dimensional structure of coral reef ecosystems like the Great Barrier Reef would be expected to deteriorate, with a massive loss of biodiversity, and ecological services and functions. Many of the concerns raised in a recent vulnerability assessment (Johnson and Marshall 2007) would become a reality, and most groups on the Great Barrier Reef would undergo major change. As argued by many other coral reef scientists (e.g. Hoegh-Guldberg et al. 2007; IPCC 2007, 2014), the increase in atmospheric carbon dioxide 500 ppm would result in scenarios where any semblance of reefs to the coral reefs of the Great Barrier Reef Marine Park today would vanish.

Figure 6 **A. If atmospheric carbon dioxide levels stabilise at current levels of 390 ppm up to around 420 ppm (scenario CRS-A), conditions will be similar to today except that mass bleaching events will be twice as common and will be more severe on reefs like the Great Barrier Reef. B. If atmospheric carbon dioxide concentrations that increase to around 450-500 ppm, together with a global temperature rise of 2°C above pre-Industrial levels, a major decline in reef-building corals is expected (reference scenario CRS-B). Because carbonate ion concentrations will fall below that required by corals to calcify and keep up with the erosion of calcium carbonate reef frameworks, reef frameworks will increasingly erode and fall apart. Seaweeds, soft corals and other benthic organisms will replace reef-building corals as the dominant organism on these much simpler reef systems. C. Levels of carbon dioxide in the atmosphere above 500 ppm, and associated temperature change (reference scenarios CRS-C) will be catastrophic for coral reefs which will no longer be dominated by corals or many of the organisms that we recognise today. Reef frameworks will actively deteriorate at this point, with ramifications for marine biodiversity, coastal protection and tourism (Reprinted courtesy of Science Magazine from Hoegh-Guldberg et al. 2007).**



47. Consistent with the available science, the GBRMPA has found that climate change is the most serious long-term risk facing the Great Barrier Reef and is likely to have far reaching consequences for the Region's environment (GBRMPA 2014: 11-6). The GBRMPA has also found that at present, global emissions are not on track to achieve the agreed global goal of limiting global temperature rises to beneath 2°C and even a 2°C rise would be a very dangerous level of warming for coral reef ecosystems, including the Great Barrier Reef, and the people who derive benefits from them (GBRMPA 2014: 11-6). The GBRMPA found that to ensure the Reef remains a coral-dominated system, the latest science indicates global average temperature rise would have to be limited to 1.2°C (GBRMPA 2014: 11-6).

CONTRIBUTION OF THE CARMICHAEL COAL MINE

48. I have been asked to specifically address how the emissions from the proposed Carmichael Coal Mine would influence the impacts of climate change and ocean acidification on the Great Barrier Reef and whether, in my opinion, the contribution of the mine to the impacts on the Great Barrier Reef is significant.

49. As we are already above the thermal threshold for damage to reef building corals and hence coral reefs, any further addition of CO_2 into the atmosphere will directly damage the Great Barrier Reef, its natural ecosystems and the future opportunities of people and businesses that depend upon its pristine and natural values. Even in 2015, temperatures are so warm that they are approaching the thermal threshold for mass coral bleaching and mortality (see Figure 3 above).

50. The thermal coal expected to be produced from the mine is estimated to be in excess of 2.326 Gt and the direct and indirect greenhouse gas emissions associated with the mine are 4.49 Gt CO_2 over the life of the mine according to the Joint Report of Dr Meinshausen and Dr Taylor.

51. Dr Meinshusen and Dr Taylor agree at paragraph 15 of their joint report that the remaining global carbon budget after 2015 is 850 Gt CO_2 for a likely chance (66% likelihood or greater) of keeping global mean temperature rises beneath 2°C. This global carbon budget and temperature rise is based on increasing atmospheric concentrations of CO_2 to approximately 450 ppm, which would be expected to result in severe damage to the Great Barrier Reef as I have explained above.

52. Given these facts, and the already very vulnerable state of the Great Barrier Reef to climate change and ocean acidification explained above, the contribution of the CO_2 emitted from the coal extracted from the mine over its lifetime represents a very significant contribution to the impacts being felt on the Great Barrier Reef and across a vast number of other ecosystems, agricultural and societal activities and concerns. The true cost of the emitted carbon from the Carmichael Mine to the Great Barrier Reef and other ecosystems, businesses and human health must be calculated and attached to any decision on whether or not to proceed with the mine. To ignore the impact of the mine, knowing that the emissions from the extracted coal are not going to be sequestered, ignores the much greater costs of the mine to people and businesses worldwide.

EXPERT'S STATEMENT – ADDITIONAL FACTS

I am not aware of any further readily ascertainable additional facts that would assist me to reach a more reliable conclusion.

DECLARATION

In accordance with rule 24F(3) of the *Land Court Rules 2000* (Qld), I confirm that:

(a) the factual matters stated in this report are, as far as I know, true; and

(b) I have made all enquiries considered appropriate; and

(c) the opinions stated in this report are genuinely held by me; and

(d) this report contains reference to all matters I consider significant; and

(e) I understand the duty of an expert the court and have complied with that duty; and

(f) I have read and understood the *Land Court Rules 2000* on expert evidence; and

(g) I have not received or accepted instructions to adopt or reject a particular opinion in relation to an issue in dispute in the proceeding.

Signed: ....
Professor Ove Hoegh-Guldberg

Date: **6 February 2015**

Address: **c/- Global Change Institute**
The University of Queensland
St Lucia Qld 4072

REFERENCES

Anthony, K.R.N., D. I. Kline, G. Diaz-Pulido, S. Dove, O. Hoegh-Guldberg. (2008) Ocean acidification causes bleaching and productivity loss in coral reef builders. *Proceedings of the National Academy of Sciences of the United States of America* 105:17442-17446.

Baker, A. C., P. W. Glynn, and B. Riegl. (2008) Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. *Estuarine, Coastal and Shelf Science* 80:435-471.

Brown, B. E. (1997) Coral bleaching: causes and consequences. *Coral Reefs* 16:S129-S138.

Bryant, D., Burke, L., McManus, J. & Spalding, M. (1998) *Reefs at Risk* World Resource Institute, Washington, DC.

Carpenter, K.E., M. Abrar, G. Aeby, R. B. Aronson, S. Banks, et al. (2008) One-third of reef-building corals face elevated extinction risk from climate change and local impacts. *Science* 321: 560-563.

Cooke, R., Erlandson, J., Estes, J.A., Hughes, T.P., Kidwell, S.M., Lange, C.B., Lenihan, H.S., Pandolfi, J.M., Peterson, C.H., Steneck, R.S., Tegner, M.J. & Warner, R.R. (2001) Historical overfishing and the recent collapse of coastal ecosystems. *Science*. 293: 629–638.

De'ath, G., J. M. Lough, and K. E. Fabricus (2009) Declining Calcification on the Great Barrier Reef, *Science*, 323(5910), 116-119.

De'ath, G., K. E. Fabricius, H. Sweatman, and M. Puotinen. (2012). The 27-year decline of coral cover on the Great Barrier Reef and its causes. *Proc Natl Acad Sci U S A* 109:17995-17999.

Deloitte Access Economics. (2013), *Economic Contribution of the Great Barrier Reef*, GBMRPA, Townsville, http://www.environment.gov.au/system/files/resources/a3ef2e3f-37fc-4c6f-ab1b-3b54ffc3f449/files/gbr-economic-contribution.pdf, accessed 5 February 2015.

Done, T. J., P. Whetton, R. Jones, R. Berkelmans, J. Lough, W. Skirving, and S. Wooldridge (2003) Global climate change and coral bleaching on the Great Barrier Reef, final report to the State of Queensland Greenhouse Taskforce, Dep. of Nat. Resour. and Min., Townsville, Australia.Doney, S., V. Fabry, R. Feely, and J. Kleypas (2009) Ocean Acidification: The Other CO2 Problem. *Annual Review of Marine Science*, 1, 169-192.

Donner, S. D., W. J. Skirving, C. M. Little, M. Oppenheimer, and O. Hoegh-Guldberg. (2005). Global assessment of coral bleaching and required rates of adaptation under climate change. *Global Change Biology* 11:2251-2265.

Dove, S., D. I. Kline, O. Pantos, F. Angley, G. W. Tyson, and O. Hoegh-Guldberg. 2013, in review. Reef calcification versus decalcification: the difference between "reduced" and "business-as-usual" CO2 emission scenarios.

Frieler, K., M. Meinshausen, A. Golly, M. Mengel, K. Lebek, S. D. Donner and O. Hoegh-Guldberg (2012) Limiting global warming to 2 °C is unlikely to save most coral reefs. *Nature Climate Change* 3, 165–170.

GBRMPA. (2014). *Great Barrier Reef Region Strategic Assessment – Strategic Assessment Report*. GBRMPA. Townsville.

Hansen, J., Sato, M., Kharecha, P., Beerling, D., Berner, R., Masson-Delmotte, V., Pagani, M., Raymo, M., Royer, D.L., and Zachos, J.C. (2008) Target atmospheric CO_2: Where should humanity aim? 2 *Open Atmos. Sci. J.* 217-231.

Hendriks, I., C. Duarte, and M. Álvarez, 2009: Vulnerability of marine biodiversity to ocean acidification: A meta-analysis. Estuarine, Coastal and Shelf Science, 86 157-164.

Hoegh-Guldberg, O. (1999) Climate change, coral bleaching and the future of the world's coral reefs. *Mar. Freshwater Res*. 50:839–866.

Hoegh-Guldberg, O., and Bruno, J. (2010) The impact of climate change on the world's marine ecosystems. *Science*, **328,** 1523-1528.

Hoegh-Guldberg, O., and Hoegh-Guldberg H. (2008) *The impact of climate change and ocean acidification on the Great Barrier Reef and its tourist industry*. Report to the Garnaut Climate Change Review, Canberra.

Hoegh-Guldberg, O., Mumby, P.J., Hooten, A. J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell D. R, Sale, P.F., Edwards, A.J., Caldeira, K., Knowlton, N., Eakin, C. M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R.H., Dubi, A., and Hatziolos, M. E., (2007) Coral Reefs under Rapid Climate Change and Ocean Acidification. *Science* 318: 1737–1742.

Hoegh-Guldberg, O., R. Cai, E. S. Poloczanska, P. G. Brewer, S. Sundby, K. Hilmi, V. J. Fabry, and S. Jung. (2014). Chapter 30. The Ocean. Pages 1655-1731 in V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White, editors. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Hughes, T. (1995) Catastrophes, phase shifts, and large scale degradation of a Caribbean coral reef. *Science.* 265: 1547–1551.

Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B.C., Kleypas, J., Lough, J.M., Marshall, P., Nyström, M., Palumbi, S.R., Pandolfi,J.M., Rosen, B., Roughgarden, J. (2003) Climate Change, Human Impacts, and the Resilience of Coral Reefs; *Science* 301: 929–933.

Hughes, T.P., Rodriques, M J., Bellwood, D.R., Ceccarelli, D., Hoegh-Guldberg, O., McCook, L., Moltschaniwskyj, N., Pratchet, M. S. (2007) Regime-shifts, herbivory and the resilience of coral reefs to climate change. *Current Biology* 17:360–365.

IPCC. (2007) *Climate Change 2007: Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

IPCC. (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel* *on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. (2013). Summary for Policymakers. Pages 1–30 in T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, editors. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. (2014). Summary for Policymakers. Pages 1-32 in C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White, editors. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

Jackson, J.B., M. X. Kirby, W. H. Berger, K. A. Bjorndal, L. W. Botsford, et al. (2001) Historical overfishing and the recent collapse of coastal ecosystems. Science 2001 Jul 27;293(5530):629-37.

Jackson, J.B.C., Kirby, M.X., Berger, W.H., Bjorndahl, K.A., Botsford, L.W., Bourque, B.J., Bradbury, R.H., Johnson J. and Marshall P. Eds. (2007) *Climate Change and the Great Barrier Reef – A Vulnerability Assessment*. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Australia.

Kleypas, J. A., and C. Langdon, 2006: Coral reefs and changing seawater chemistry, Chapter 5 Coral Reefs and Climate Change: Science and Management. AGU Monograph Series, Coastal and Estuarine Studies, J. Phinney, O. Hoegh-Guldberg, J. Kleypas, W. Skirving, and A. E. Strong, Eds., Geophys. Union, 73-110.

Kleypas, J. A., McManus, J. W., and Menez, L. A. B. (1999). Environmental limits to reef development: where do we draw the line? *American Zoologist* 39, 146–59.

Kleypas, J. A., R. A. Feely, V. J. Fabry, C. Langdon, C. L. Sabine, and R. R. Robbins, 2006: Impacts of ocean acidification on coral reefs and other marine calcifiers: A guide for future research, Report of a workshop held 18-20 April 2005, St Petersburg, FL, sponsored by NSF, NOAA and the US Geological Survey, 88pp.

Kroeker, K. J., R. L. Kordas, R. Crim, I. E. Hendriks, L. Ramajo, G. S. Singh, C. M. Duarte, and J. P. Gattuso. (2013). Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global Change Biology* 19:1884-1896.

Levitus, S., J. I. Antonov, T. P. Boyer, R. A. Locarnini, H. E. Garcia, and A. V. Mishonov (2009), Global ocean heat content 1955-2008 in light of recently revealed instrumentation problems, *Geophysical Research Letters, 36*.

Llewellyn, L. (2010), Revisiting the association between sea surface temperature and the epidemiology of fish poisoning in the South Pacific: Reassessing the link between ciguatera and climate change, Toxicon, 56, 691-697.

Lough, J. (2007) Climate and climate change on the Great Barrier Reef. Chapter 2 In: *Climate Change and the Great Barrier Reef A Vulnerability Assessment*. Johnson J and Marshall P Eds. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Australia.

McCulloch, M.T., Fallon, S., Wyndham, T., Hendy, E., Lough, J., and Barnes, D. (2003). Coral record of increased sediment flux to the inner Great Barrier Reef since European settlement. *Nature* 421 (6924): 727–730.

Munday, P. L., Jones, G.P., Sheaves, M., Williams, A.J., and Goby, G. (2007) Vulnerability of fishes of the Great Barrier Reef to climate change. Chapter 12 In: *Climate Change and the Great Barrier Reef A Vulnerability Assessment*. Johnson J and Marshall P Eds. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Australia.

National Oceanic & Atmospheric Administration (NOAA) (2015), Trends in atmospheric CO_2 – recent Mauna Loa CO_2, http://www.esrl.noaa.gov/gmd/ccgg/trends/, accessed 5 February 2015.

Pelejero, C., E. Calvo, and O. Hoegh-Guldberg (2010), Paleo-perspectives on ocean acidification, Trends in Ecology & Evolution doi: 10.1016/j.tree.2010.1002.1002.

Raven, J., Caldeira, K, Elderfield, H., Hoegh-Guldberg, O., Liss, P, Riebesell, U., Shepherd, J., Turley, C., Watson, A. (2005) *Ocean acidification due to increasing atmospheric carbon dioxide*. *Royal Society Special Report*, The Royal Society. London.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Shellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A. (2009) A safe operating space for humanity. *Nature* 461:472-475.

Strong, A.E., Liu G, Meyer J, Hendee JC, Sasko D (2004) Coral Reef Watch 2002. Bulletin of Marine Science 75: 259-268.

Veron, J.E.N., Hoegh-Guldberg, O., Lenton, T.M., Lough, J.M., Obura, D.O., Pearce-Kelly, P., Sheppard, C.R.C., Spalding, M., Stafford-Smith, M.G., Rogers, A.D. (2009) The coral reef crisis: The critical importance of <350 ppm CO_2. *Marine Pollution Bulletin*, **58,** 1428-1436.

Wilkinson, C. (ed.), (2004), *Status of coral reefs of the world: 2004*. Volume 1. Australian Institute of Marine Science, Townsville. 301 p.

APPENDIX 1

Curriculum vitae of Professor Ove Hoegh-Guldberg

OVE HOEGH-GULDBERG

GLOBAL CHANGE INSTITUTE

University of Queensland

NATIONALITY

Australian (born: 26/9/59, Sydney)

EDUCATION

1989	Ph.D. University of California, Los Angeles
1982:	B.Sc. (Hons, 1st class) University of Sydney

CURRENT POSITIONS

Director, Global Change Institute, University of Queensland (2010 –present)
Deputy Director, ARC Centre for Excellence for Reef Studies (2006-present)
Professor of Marine Studies, University of Queensland (2000-present)
Affiliated Researcher, Centre for Ocean Solutions, Stanford University (2008-present)

SIGNIFICANT APPOINTMENTS

2013-present	Fellow, Australian Academy of Science
2013-2014	Global Partnership for Oceans, Chair, Blue Ribbon Panel
2010-2014	Coordinating Lead Author, "Oceans" Chapter, 5th Assessment Report, Intergovernmental Panel on Climate Change (IPCC)
2012-present	Global Partnership for Oceans, Interim Committee member
2014-present	Chair, Technical Advisory Committee, Great Barrie Reef Foundation
2012-present	Chief Scientist, Catlin Seaview Survey
2001-2010	Visiting Professor, Stanford University
2001-2010	Director and Founder, Stanford Australia Marine Program, UQ
2010-2013	Senior Executive Management Committee, University of Queensland
2006-2012	Member, Board of Reviewing Editors, Science Magazine
2000-2009	Director and Founder, Centre for Marine Studies, University of Queensland
2001-2009	Chair, Climate Change and Coral health working group within CRTR project, Global Environmental Facility -World Bank (www.gefcoral.org).
2006-present	Member, Royal Society, London, Marine Advisory Network (MAN)
2004-present	Founding Member, Australian Climate Group now Climate Science Australia

2000-present: Member, International Scientific Advisory Committee, GBR Foundation
2004-2007 Member, Royal Society, London, Working Group on Ocean Acidification
2001-2005 Member, UNESCO-World Bank-IOC Synthesis Panel TRG Coral research.
2000-2009 Director, Heron Is, Low Isles and Morton Bay Research Stations
2002-2006 Member, Scientific Advisory Committee, QLD Gov committee on Biodiversity
1998 Visiting scientist, European Oceanographic Center, Monaco
1998 Research faculty, Indiana Institute of Molecular Biology
1995-1999 Director, One Tree Island Research Station
1993-1997 Director and Founder, Coral Reef Research Institute
1989-1991 Postdoctoral Fellow, Office of Naval Research, University of Southern California
1987-1991: Director and joint company founder, Sable Systems Pty Ltd
1983-1987: NAUI Dive Instructor, UCLA Dive School

HONORS AND AWARDS

2014	American Society of Microbiologists, ASM Lecturer for 2014
2013	ARC Laureate Fellowship (2013-2018)
2008	Queensland 2008 Smart State Premier's Fellow (2008 - 2013)
2011-2014	Highly Cited Researcher (Thomson Reuters, 4 years in a row)
2012	Citation Award Winner, Thomson Reuters Citation & Innovation Award (top-cited author: Highest cited author in Ecology)
2010	Thomson Reuters' ISI Highly Cited Researchers (most cited Australian scientist in the area of Climate Change, 3rd most cited internationally)
2009	Whitley Certificate of Commendation for book on Great Barrier Reef
2009	Thomson-Reuters' ISI Hot Paper Award.
2009	Wesley College Foundation (University of Sydney) Medal 2009
1999	The 1999 Eureka Prize for Scientific Research
1996	Sydney University Award for Excellence in Teaching
1989	Robert D. Lasiewski Award (for Ph.D., UCLA)
1988	UCLA Distinguished Scholar Award 1988
1987	Australian Museum/Lizard Island Bicentenary Fellowship
1987	Departmental Fellowship Award, UCLA
1984-88	Sydney University Traveling Scholarship (Ph.D. scholarship to U.S.)

INSTITUTE WEBSITE: WWW.GCI.UQ.EDU.AU

LAB WEBSITE: WWW.CORALREEFECOSYSTEMS.ORG

PROFESSIONAL SOCIETIES AND BOARD MEMBERSHIP

Science Magazine (Board of Reviewing Editors, 2006-2012)

Technical Advisory Committee, Great Barrier Reef Foundation (Chair, 2014-present)
Great Barrier Reef Foundation (International Scientific Advisory Committee; 2000-present)
Biodiversity Research Centre Academia Sinica, Taipei (Advisory Board; 2010 - present)
Leibniz Center for Tropical Marine Ecology, Bremen (Advisory Board; 2010 - present)
International Symbiosis Society (Governing Councilor, 2004-present)
Australian Coral Reef Society (Council 2000-2008; President; 2000-2002)
International Society for Reef Studies (Council; 2002-2008)

BIOGRAPHICAL SKETCH

Ove Hoegh-Guldberg is the Director of the Global Change Institute (www.gci.uq.edu.au), Deputy Director of the Centre for Excellence in Coral reef Studies (www.coralcoe.org.au) and Professor of Marine Science (www.coralreefecosystems.org) at the University of Queensland in Brisbane, Australia. Ove's research focuses on the impacts of climate change on marine ecosystems, and is one of the most cited authors on climate change with more than 15,000 citations from > 250 papers, books, and patents). He has also been a dedicated communicator of the threat posed by ocean warming and acidification to marine ecosystems, first raising the alarm with respect to seriousness of climate change for coral reefs in a landmark paper published in 1999. In addition to leading a research group at the University Queensland, he is the Coordinating Lead Author for the 'Oceans' chapter for the Fifth Assessment report of the Intergovernmental Panel on Climate Change. Working with Sir David Attenborough, Sylvia Earle, Tom Brokaw, Philippe Cousteau and many others, Ove has also sort to communicate crucially important scientific messages beyond the walls of academia. He has been awarded a Eureka Prize for his scientific research and a QLD Premier's fellowship, and is currently an ARC Laureate Fellow and member of the Australian Academy of Science. He shares his life with UQ marine biologist Associate Professor Sophie Dove and their two ocean enthusiast children, Fiona and Chris.

Access to report from Ove's term as Queensland Smart State Premier's Fellow can be found here (2008-2013; http://www.gci.uq.edu.au/images/uploads/publications/pf-report.pdf).

Refereed articles

Over 246 peer-reviewed publications (31 in Science, Nature or PNAS), with 56 since the beginning of 2012 together with over 30 peer-reviewed book chapters, research reports and 2 international patents. Publications include major contributions to physiology, ecology, environmental politics, and climate change. My most significant scientific contributions have been recognized recently through invited reviews by leading journals such as Science (Hoegh-Guldberg and Bruno 2010; Hoegh-Guldberg *et al.* 2007), major research funding (>$30 million since 2000; ARC Centre for Excellence, Queensland Smart State Premier's Fellowship; ARC Laureate Fellowship) and my appointment as Coordinating Lead Author of Chapter 30 ("The Oceans") for the 5th

Assessment Report of the Intergovernmental Panel on Climate Change. I am currently the most cited Australian author (and 3rd internationally out of 53,136 authors) on the subject of "climate change" according to the Thomson-Reuter's ISI Web of Science (2011, sciencewatch.com/ana/st/climate/authors). This represents a group of less than 0.5% of all published researchers in the world. I received a major award from Thomson Reuters in 2012 (Citation Award Winner in Ecology Thomson Reuters Citation & Innovation Award). My research publications have been cited over 24,209 times (Thompson-Reuters) and is cited over 2,000 times per year. My H-index is 55 (ISI 2011) or 67 (Google Scholar) and I have received several awards from Thomson-Reuters ISI Web of Science for papers that are among ISI's hottest paper (most cited over the past two years) in the both the area of "climate change" and "ocean acidification" (sciencewatch.com/ana/fea/09novdecFea/). In addition to my 115 peer-reviewed journal publications (29 in Science, Nature, PNAS) produced since 2006, I have also produced the edited book (Hutching, Kingsford and Hoegh-Guldberg, "The Great Barrier Reef", Springer/CSIRO Publishing; winner of a Whitley Award commendation in 2009) and 11 book chapters and refereed reports, and continue to hold 2 international patents (together Sophie Dove) on a novel class of Green Fluorescent Pigments. I have received several major prizes, including the UCLA Distinguished Scholar Award and the 1999 Eureka Prize for discovering the molecular mechanism (see below) behind mass coral bleaching and mortality (Hoegh-Guldberg and Jones 1999; Hoegh-Guldberg and Smith 1989a; Hoegh-Guldberg and Smith 1989b) and impact of global climate change on the earth's coral reefs (Hoegh-Guldberg 1999). These early discoveries shaped my career which has increasingly focused on the impact of global climate change on the marine ecosystems and the implications for people and societies (Hoegh-Guldberg *et al.* 2009). Recent awards include being in The Conversation's top ten articles in 2011 (http://theconversation.edu.au/the-conversations-top-ten-articles-in-2011-4929) and receiving a Thomson Reuters award a major citation award (top 12 scientists in Australia in "recognition of their outstanding contribution on research" (across all fields). http://ip-science.thomsonreuters.com.au/citation_innovation_awards_2012/).