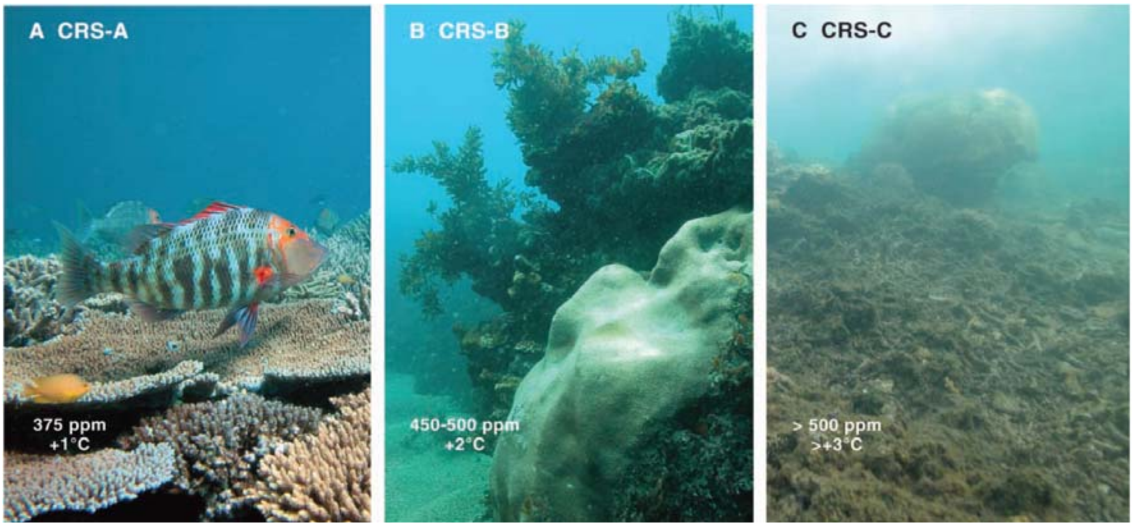
The current and future impacts of climate change and ocean acidification on the Great Barrier Reef



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

Reference numbers:
MRA092-11 & EPA093-11 (MLA 50229)
MRA098-11 & EPA099-11 (MLA 50230)
MRA105-11 & EPA106-11 (MLA 50231)

Professor Ove Hoegh-Guldberg
Director, Global Change Institute
The University of Queensland

3 August 2011

Table of Contents

INTRODUCTION

1. I have been asked by the Friends of the Earth – Brisbane Co-Op Ltd (FoEB) to provide an expert opinion of the likely ecological impacts of climate change and ocean acidification on the Great Barrier Reef, Australia.

2. This report has been prepared in response to that request for use in an objection hearing in the Land Court concerning a large open-cut coal mine. The mine is the Wandoan Coal Mine, an open-cut coal mine proposed to operate for 30 years west of the township of Wandoan, approximately 350 km northwest of Brisbane in the Surat Basin, Queensland (the mine).

3. The thermal coal deposits for the mine are estimated to be in excess of 1.2 billion tonnes, and are located within three Mining Lease Applications (MLAs 50229, 50230 and 50231), which comprise approximately 32,000 hectares. The coal from the mine is proposed to be crushed, processed and blended on site before being transported by rail to port for export or, possibly, for domestic use. The thermal coal produced by the mine is intended to be sold to other companies to be burnt in coal-fired power stations to generate electricity.

4. The Wandoan Coal Project environmental impact statement and an accompanying technical report on greenhouse gas emissions calculated that the emissions from the mining and use of the coal from the mine would be over 41 million tonnes of carbon dioxide equivalents annually and 1.3 billion tonnes of carbon dioxide equivalents over the life of the mine (Xstrata Coal 2008).

5. For the purposes of preparing this report I have been provided with a copy of the objection lodged by FoEB 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.

6. To balance brevity and comprehensiveness I have prepared this report as a summary of critical information and attached for further reference (if required) copies of Hoegh-Guldberg (1999), Hoegh-Guldberg et al. (2007), Veron et al. (2009) and Hoegh-Guldberg and Bruno (2010).

RELEVANT EXPERTISE

7. 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. 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 coral reefs and related marine ecosystems;

   (c) coral bleaching and its 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.

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

9. In preparing my report I understand my duty as an expert witness before the Court based on rule 426 of the *Uniform Civil Procedure Rules* 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

10. 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.

11. 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 (Fig. 1).

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

12. 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.

13. 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 (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 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)**

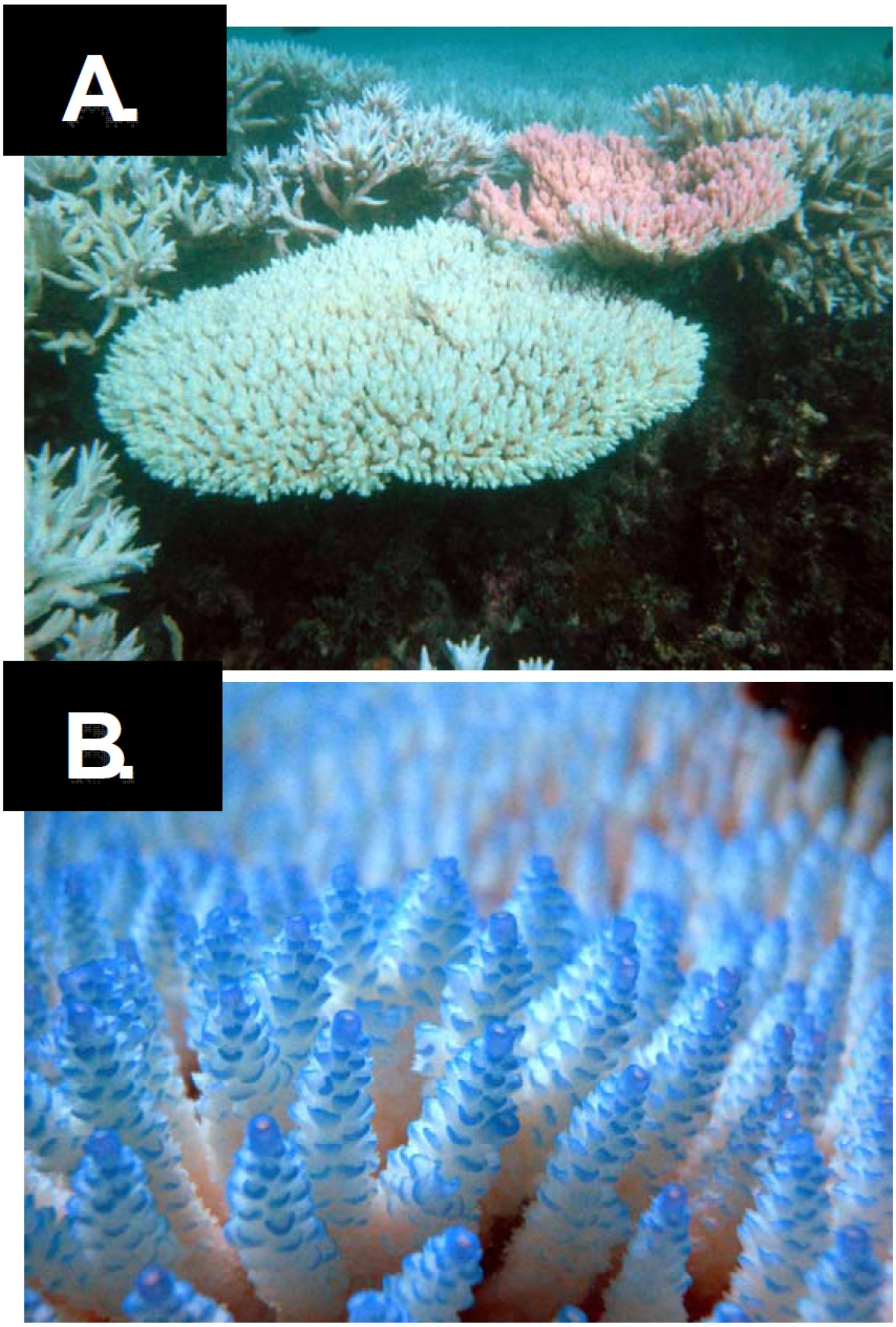
CLIMATE CHANGE AND OCEAN ACIDIFICATION

14. 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. 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). 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). Increasing atmospheric carbon dioxide 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). 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 (Hendriks et al. 2009; Kleypas; Langdon 2006; Kleypas et al. 2006; Raven et al. 2005). In addition to the size of the absolute change, global conditions have varied at unprecedented rates of change. Changes in atmospheric carbon dioxide (hence carbonate ion concentrations) 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).

15. 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). Coral bleaching (Fig. 2) occurs when the symbiosis between corals and their critically important dinoflagellate symbionts breaks down. These symbionts provide most of energy needs of the coral host. The breakdown of the symbiosis can occur for a number of reasons, 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. 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).

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**

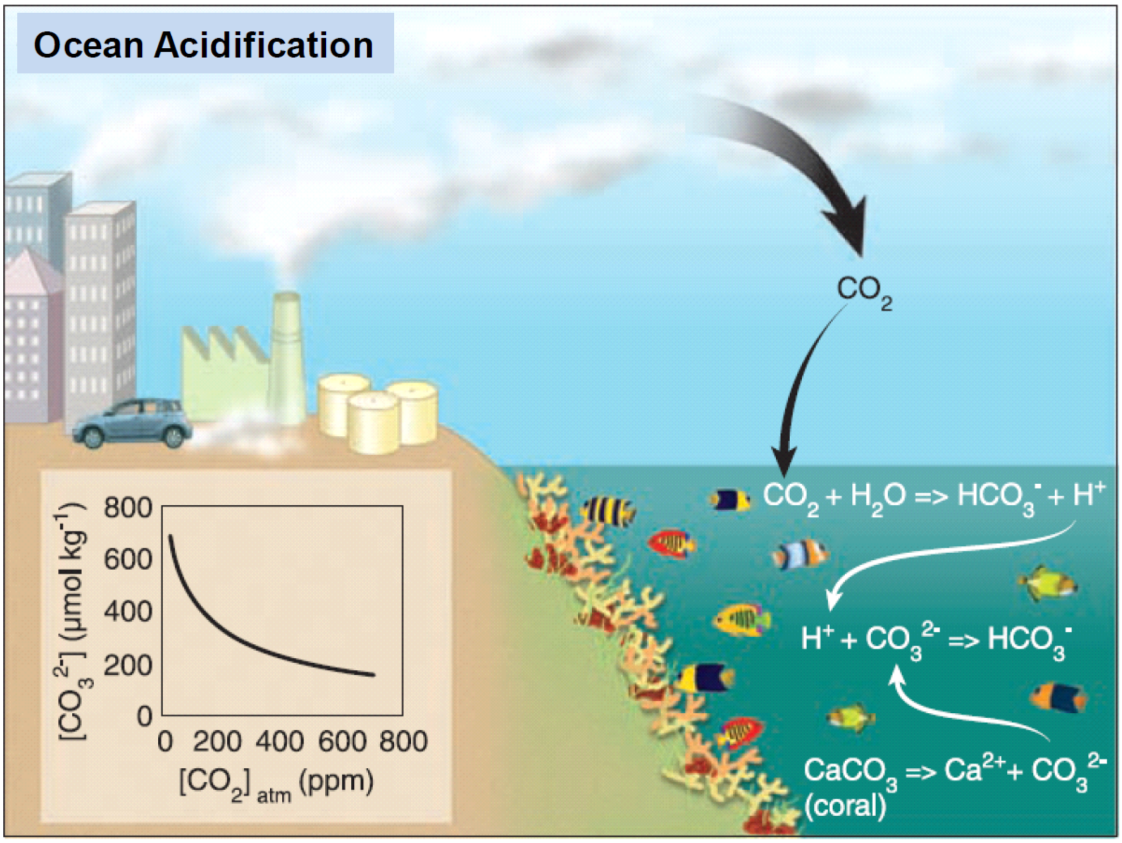


16. The Great Barrier Reef has been affected by coral bleaching as a result of heat stress six times over the past 25 years. Recent episodes (i.e. 1998, 2002) on the Great Barrier Reef have been the most intense and widespread. In 1998, the Great Barrier Reef experienced what was considered at the time 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 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 2007, 2011).

17. The changes to water chemistry arising from ocean acidification, are adding additional pressure on coral reefs. Increasing concentrations of atmospheric carbon dioxide is 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 3). 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 conditions (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. 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).

Figure 3 **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)**



IMPACTS AT CURRENT LEVELS OF CO_2

18. 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 390 parts per million (ppm) at present based on observations at the Mauna Loa observatory in Hawaii after season fluctuations are accounted for (NOAA 2011). 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). 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.

19. 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 ~390 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).

20. 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 must be an international imperative (Hoegh-Guldberg and Bruno 2010). 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

21. 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 depend upon the level at which atmospheric CO_2 is stabilised.

22. 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 emissions 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

23. 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). These changes are occurring at rates which dwarf even the most rapid changes seen over the past million years. 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 carbon dioxide 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. 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 change rapidly over the coming decades (IPCC 2007, Done et al. 2003, Donner et al. 2005).

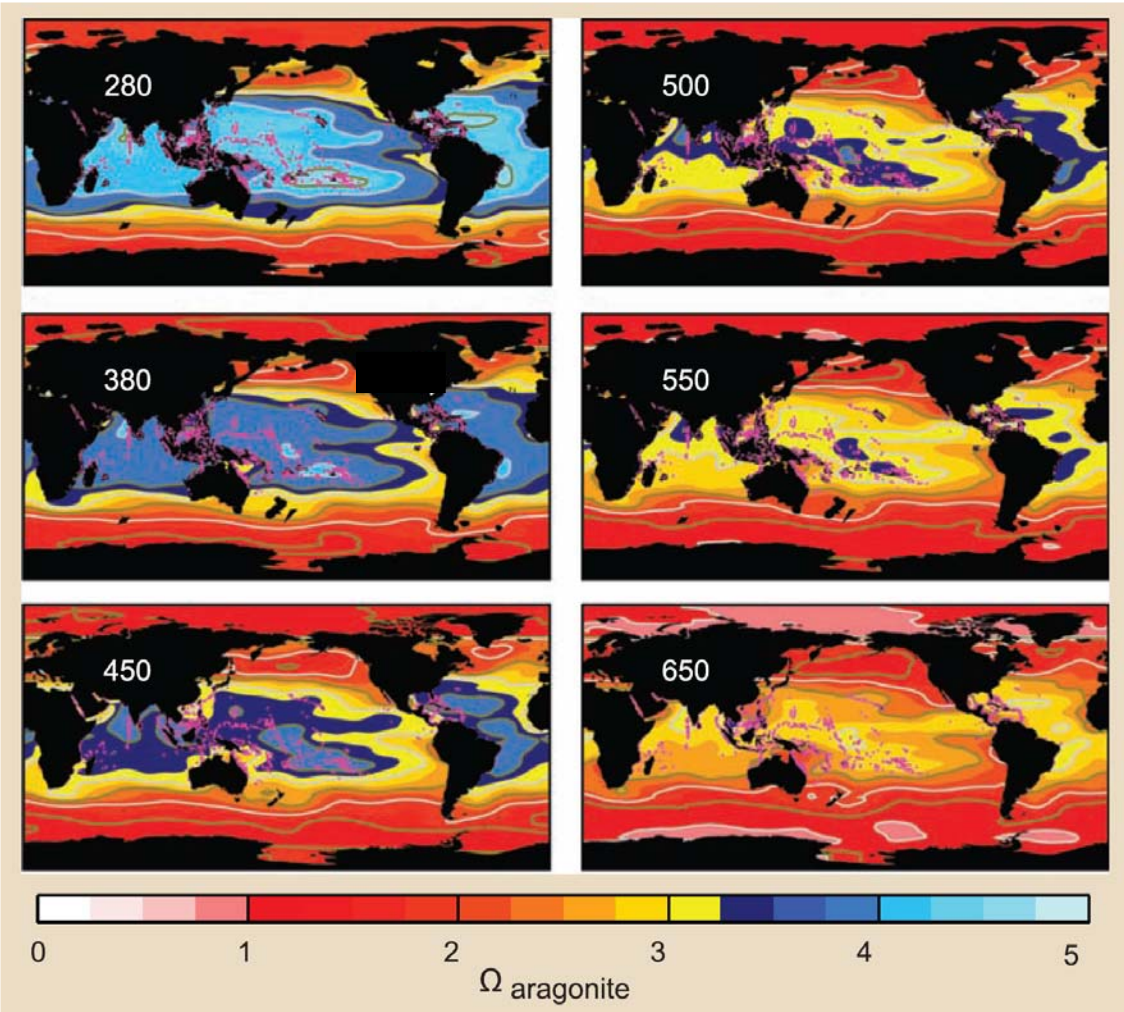
24. Consideration has recently been given to how reef systems like the Great Barrier Reef will change in response to changes in atmospheric gas composition. In this regard, a recent paper (Hoegh-Guldberg et al. 2007) concluded that carbonate coral reefs such as the Great Barrier Reef are unlikely to 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 (Fig. 4).

25. Taking the two drivers together allows the scientific community to project of 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 (fisheries, tourist use) are severely degraded at this point.

26. 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 5).

27. It is important that the three scenarios in Figure 5 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 4 **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).**



28. 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.

29. 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), 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.

30. Secondly, there is likely to be a shift towards reduced three-dimensional reef frameworks as concentrations of carbonate ions decrease and become limiting for the calcifying activities of corals. 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.

31. 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).

32. 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.

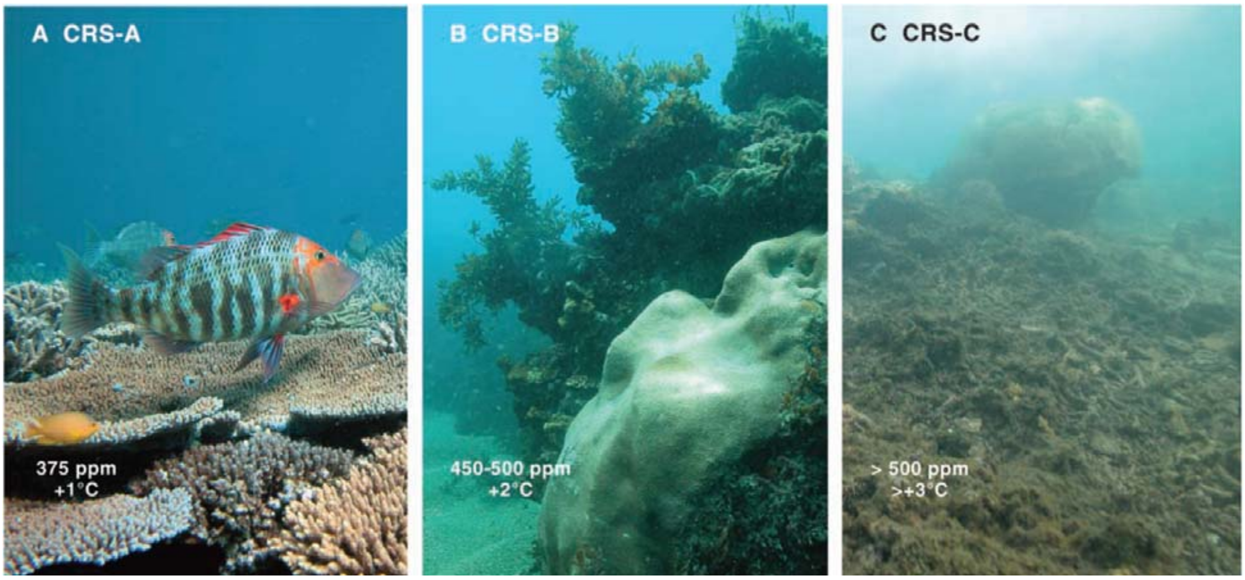
33. The loss of the three-dimensional structure has significant implications for other coral reef dwelling species such as fish populations where at least 50% of the fish species are likely to disappear with the loss of the reef-building corals and the calcium carbonate framework of coral reefs (Munday 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 (Fig 5B).

34. 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).

35. 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 (Fig 4C). 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), 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 5 **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 recognize 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).**



CONTRIBUTION OF THE WANDOAN COAL MINE

36. I have been asked to specifically address how would the emissions from the proposed Wandoan Coal Mine 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.

37. 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. Given that the thermal coal deposits for the mine are estimated to be in excess of 1.2 billion tonnes, the CO_2 emissions associated with the mine will generate 41 million tonnes of carbon dioxide equivalents annually and 1.3 billion tonnes of carbon dioxide equivalents over the life of the mine (Xstrata Coal 2008). Given that the cumulative emission of more than 1080 GT of CO_2 (see the report from Dr Malte Meinshausen) from now onwards will have a greater than 50% probability of driving atmospheric CO_2 beyond 450 ppm, the 1.3 GT 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

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 are not going to be sequestered, ignores the much greater costs of the mine to people and businesses worldwide.

38. In summary, the Great Barrier Reef provides enormous benefits and income to the Australian people. 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 (global warming and ocean acidification), with the latter (global climate change) 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 thousands if not millions of years, and is having a direct impact on the health of the Great Barrier Reef by driving unprecedented mass coral bleaching and mortality events, and causing calcification rates to decline in response to declining carbonate ion concentrations. The addition of further carbon dioxide to the atmosphere by enterprises such as the Wandoan 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 carbon dioxide continues to increase at its current rate. Coal mining operations such as the Wandoan mine will result in highly 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.

DECLARATION

In accordance with rule 428 of the *Uniform Civil Procedure Rules* 1999 (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) there are no readily ascertainable additional facts that would assist me in reaching more reliable conclusions; and

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

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

(f) I understand that my duty is to assist the Court and that it overrides any obligation I may have to any party to the proceeding or to any person who is liable for my fees or expenses; and

(g) I have complied with my duty to assist the Court.

Signed: Ove Hoegh-Guldberg ....
Professor Ove Hoegh-Guldberg

Date: Aug 4, 2011 ....

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

REFERENCES

Anthony KRN, Kline DI, Diaz-Pulido G, Dove S, Hoegh-Guldberg O (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

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 KE, Abrar M, Aeby G, Aronson RB, Banks S, 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. Il Calcification on the Great Barrier Reef, Science, 323(5910), 116-119.

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., Skirving, W.J., Little, C.M., Oppenheimer, M., and Hoegh-Guldberg, O. (2005). Global assessment of coral bleaching and required rates of adaptation under climate change. Glob. Change Biol. 11, 1–15.

GBRMPA (2007) Great Barrier Reef Climate Change Action Plan 2007 – 2011. http://www.gbrmpa.gov.au/__data/assets/pdf_file/0012/22620/climate-change-action-plan.pdf

GBRMPA (2011) Great Barrier Reef Marine Park authority webpage (accessed August 2, 2011) http://www.gbrmpa.gov.au/corp_site/info_services/publications/sotr/latest_updates/corals/part_04.html

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.

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

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.

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

Jackson JB, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, 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., 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.

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) (2011), Trends in atmospheric CO_2 – recent Mauna Loa CO_2, http://www.esrl.noaa.gov/gmd/ccgg/trends/, accessed 27 June 2011.

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*, pp 68; ISBN 0 85403 617 2.

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 AE, 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.

Xstrata Coal (2008), *Wandoan Coal Project Environmental Impact Statement*, Parsons Brinckerhoff Australia Pty, Brisbane, Vol 1, Book 2, Ch 14 (Greenhouse gases and climate change); and Clarke S (2008), Technical Report – Wandoan Coal Project greenhouse gas assessment, URS, Brisbane.

APPENDIX 1

Curriculum vitae of Professor Ove Hoegh-Guldberg

OVE HOEGH-GULDBERG

GLOBAL CHANGE INSTITUTE

University of Queensland

NATIONALITY

Australian (born: 26/9/59)

EDUCATION

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

CURRENT POSITIONS

Professor of Marine Studies, University of Queensland
Director, Global Change Institute, University of Queensland
Deputy Director, ARC Centre for Excellence for Reef Studies
Scientific advisor, Centre for Ocean Solutions, Stanford University
Visiting Professor, Stanford University

SIGNIFICANT APPOINTMENTS

2010-present Coordinating Lead Author, "Oceans" chapter, 5th Assessment Report, IPCC.
2010-present Senior Executive Management Committee, University of Queensland
2006-present Member, Board of Reviewing Editors, Science Magazine
2000-2009 Director, Centre for Marine Studies, University of Queensland
2000-2010 Director, Stanford Australia Program
2001-2009 Chair, Global Environmental Facility -World Bank-Intergovernmental Commission (IOC) Working group on climate change and coral health (www.gefcoral.org).
2006-present Member, Royal Society, London, Marine Advisory Network (MAN)
2001-present: Member, International Scientific Advisory Committee, GBR Foundation
2004-present Deputy Director, ARC Centre for Excellence in Reef Studies (www.coralcoe.org.au)
2004-present Founding Member, Australian Climate Group now Climate Science Australia
2004-2007 Member, Royal Society, London, Working Group on Ocean Acidification
2001-2008 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

1995-99: Director, One Tree Island Research Station
1993-97: Director and Founder, Coral Reef Research Institute
1987-1991: Director and joint company founder, Sable Systems Pty Ltd
1983-1987: NAUI Dive Instructor, UCLA Dive School

HONORS AND AWARDS

2009: Queensland 2008 Smart State Premier's Fellow (2008 - 2013)
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.)

PROFESSIONAL SOCIETIES

Science Magazine (Board of Reviewing Editors, 2006-present)
Great Barrier Reef Foundation (International Advisory Committee; 2000-present)
Biodiversity Research Centre Academia Sinica, Taipei (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)

RECENT ADMINISTRATIVE RESPONSIBILITIES

INSTITUTE DIRECTOR – GLOBAL CHANGE INSTITUTE (SINCE 2010)

CENTRE DIRECTOR – THE CENTRE FOR MARINE STUDIES – UNIVERSITY OF QUEENSLAND (2000-2010)

DIRECTOR, STANFORD AUSTRALIA PROGRAM (STANFORD UNIVERSITY; (2001-2010)

CHAIR, GEF BLEACHING TARGETED RESEARCH GROUP - INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION (IOC) AND WORLD BANK COASTAL PROGRAM

CORAL REEF ECOSYSTEMS LABORATORY (WWW.CORALECOSYSTEMS.ORG**)**

PUBLICATIONS: OVE HOEGH-GULDBERG

Refereed articles

I have published a total of 190 peer-reviewed publications (19 in the prestigious journals Science, Nature and PNAS), with 50 since 2009. I have also published over 30 peer-reviewed book chapters, research reports and 2 international patents. My work has been cited over 6,874 times and I have an H-index is 35 (ISI 2011). In addition to my full-length peer-reviewed journal publications, I have produced the edited book ("The Great Barrier Reef", Springer/CSIRO Publishing) and another 20 full length research reports or conference papers, 2 international patents, and 459 contributions to science debate via my science blog site (www.climateshifts.org). I am ranked among to the top most cited authors in the research area of global warming in 2006 and was profiled on the ISI special topics interview (http://www.esi-topics.com/gwarm 2006/ interviews/OveHoegh-

Guldberg.html). Three of my papers are now 1st, 4th and 6th most cited papers over the past 10 years in the area of "climate change". Citation rates are 1,594 (Walther et al. 2002), 868 (Hoegh-Guldberg 1999), and 714 (Hughes et al. 2003). Three of his papers are now 1st, 4th and 6th most cited papers over the past 10 years in the area of "climate change". My recent paper in Science in Dec 2007 is now ISI's hottest paper in the both the area of "climate change" and "ocean acidification" (cited 392 times in < 4 years). I recently received a major award from Thomson Reuters ISI for being "Highly Cited" and the 2007 Science paper has received an award from Essential science indicators. I have been profiled on science watch.com (www.sciencewatch.com/dr/nhp/2009/09jannhp/09jannhpGuld/) as a result of this achievement and have won several awards for my scientific productivity.

A list of my published material can be provided on request.

APPENDIX 2

Copies of main references

The following are attached if further reference is required to supplement the main section of this report:

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., 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.

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

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

Note: these references were removed to respect copyright. The original version of this report was 72 pages in length.