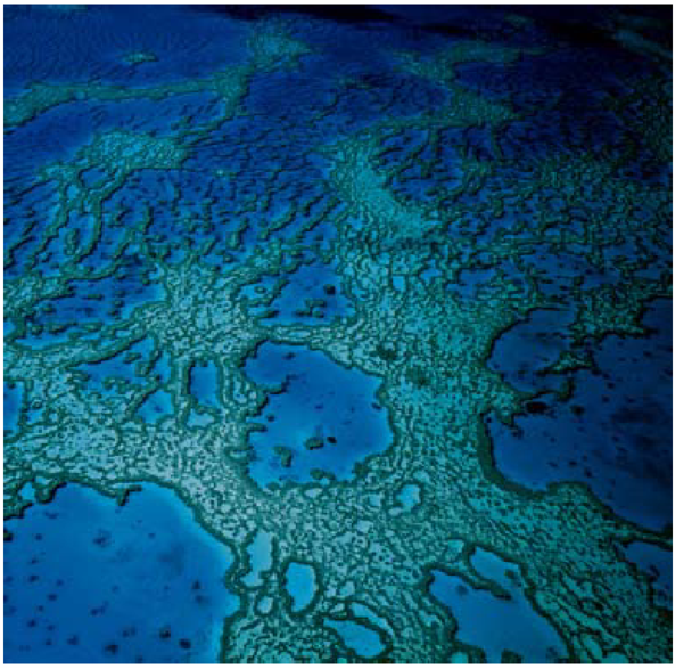
Likely ecological impacts of global warming and climate change on the Great Barrier Reef by 2050 and beyond



Report prepared for an objections hearing in the Queensland Land and Resources Tribunal

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EXECUTIVE SUMMARY

1. This report considers the likely ecological impacts of global warming and climate change on the Great Barrier Reef, Australia, by 2050 and beyond. It has been prepared at the request of the Queensland Conservation Council (QCC) for use in an objections hearing before the Queensland Land and Resources Tribunal concerning a proposed large open-cut coal mine.

2. The earth is undergoing accelerating climate change that is being driven by rapidly increasing greenhouse gas concentrations. This is changing the conditions under which the earth's fauna and flora have flourished over the past several million years. There is now extensive evidence of changes to the distribution, abundance and health of earth's terrestrial and aquatic ecosystems. Species are migrating towards the poles, ecosystems like coral reefs are experiencing increasing stressful conditions and populations of organisms are in decline as a result of a combination of climate change and other anthropogenic impacts.

3. There is no longer any serious doubt that the earth has warmed by 0.6-0.8 degrees Celsius since 1880 and will warm a further 2-6 degrees Celsius by 2100, almost exclusively due to human activity. Atmospheric concentrations of carbon dioxide are now 100 parts per million above those seen over the past 650,000 years, and rates of increase are 2-3 orders of magnitude above most of those periods in which the temperature of the planet changed. It is probable that these conditions also exceed those seen for many millions of years. Past changes to greenhouse gas concentrations have always been directly accompanied by increases in global temperature. It is no longer credible to claim that there is "major debate around the fact of human driven climate change". It is here right now and is already changing our lives. It will continue to do so for many hundreds of years.

4. The earth's biological systems are already responding to the minimal warming seen so far. Terrestrial bird, butterfly and plant populations have shifted 50-200 km towards the poles. The tree lines of many alpine forests have expanded to higher altitudes and exotic species have invaded as the number of frost days has decreased. Rainforests are severely threatened and palm forests now grow in alpine Switzerland.

5. Reproductive seasons have lengthened for animals and plants over the entire planet. Similar changes are occurring in the sea. Many regions of the world are experiencing the invasion of warm water benthic fish and invertebrate species into reefs at higher latitudes. Shifts in the structure of planktonic and intertidal communities show similar patterns with major changes being documented over the past 100 years. The melting of the earth's polar ice caps is rapidly changing the habits and distributions of both Arctic and Antarctic biota.

6. Coral reefs have shown some of the most dramatic impacts of climate change, with the advent of worldwide coral bleaching events from 1979 as the thermal threshold of corals have been exceeded. Reports of global cycles of coral bleaching and mortality have increased dramatically. The global episode of mass coral bleaching in 1998 was the largest in recorded history, and coincided with the warmest year and decade on record. It removed an estimated 16% of the world's living coral, with

estimates for the Indian Ocean rising as high as 46% of living coral dying over a few months.

7. Coral reefs across the world are also deteriorating due to a combination of coastal land practices, overfishing and marine based pollution. These influences alone have been estimated to potentially remove over 50% of coral reefs over the next 30-50 years. Reduced carbonate alkalinity of seawater (the source of ions for calcification) is inflicting additional pressure on coral reefs.

8. This will have dramatic impacts on the world's coral reefs over the next 50 years. It will reduce coral abundance to less than 5%, will cause major changes to fish populations and will change the natural values of coral reefs to millions of reef users and associated industries. These changes will add to the problems of global fishing industries which are already in crisis as fish stocks plummet.

9. Australia's Great Barrier Reef is arguably the best-managed reef ecosystem in the world; yet this does not prevent it from being under great threat from continued warming of sea temperatures. It also faces growing threats from coastal land practices and exploitation of fisheries resources. The facts supporting these conclusions are indisputable.

10. Change to the health of our ecosystems as a result of climate change is inevitable. Even under the best case scenario, losses of at least 50% of the Reef's living coral cover are likely to occur by 2050. It is estimated that corals on the Great Barrier Reef will experience between 2 degrees Celsius and 6 degrees Celsius increases in sea temperature by 2100. Torres Strait temperatures will be found at the southern Great Barrier Reef as early as 2030. As with coral reefs elsewhere, thermal stress is likely to increase to levels that are several times higher than in 1998. By the middle of this century, these levels will be exceeded every year at all sites along the Great Barrier Reef. Corals will either have to adapt or move. If they don't do either, then corals will become rare over most of the Great Barrier Reef.

11. There is little to no evidence that corals can adapt fast enough to match even the lower projected temperature rise. Most evidence points to rates of adaptation that involve centuries and millennia. There is no evidence that coral can take on completely new varieties of symbiotic dinoflagellates with the result that they are hardened to the projected increases in sea temperature. Reefs do not exchange masses of larvae over hundreds of kilometres even though they are connected genetically. These factors plus the observation that mass mortalities of corals are increasing in response to sea temperature increases suggest that the rate of adaptation cannot match the high rate of climate change currently occurring.

12. The flora and fauna of the Great Barrier Reef is going to change dramatically if current estimates of climate change are correct. The past behaviour of coral reefs to warming has revealed that thermal stresses of 5 degree heating months remove the majority of reef-building corals and other related organisms. There is no evidence to the contrary. The Great Barrier Reef will see thermal stresses of 5 or more degree heating months on an annual basis by 2050. They are projected to rise to as high as 15-20 degree heating months by 2100. Coral cover will decrease to less than 5% on most reefs by the middle of the century under even the most favourable assumptions. This is the only plausible conclusion if sea temperatures continue to

rise. Reefs will not disappear but they will be devoid of coral and dominated by other less appealing species such as macroalgae and cyanobacteria.

13. The rapid reduction in coral cover will have major consequences for other organisms and reef functions. Many organisms that are coral dependent will become rare and may become locally or globally extinct. Other organisms, such as herbivores, may actually increase as reefs change from coral domination to algal/cyanobacterial domination. Fish and other organisms that form the basis of fisheries will change, although the direction of this change has yet to be determined and will depend on how reefs are treated with respect to other anthropogenic stresses. Increases in the abundance of cyanobacteria may have implications for the incidence of ciguatera poisoning, a major problem in some areas of the world already.

14. Coral reefs have deteriorated due to a combination of anthropogenic misuse and climate change induced bleaching events such as those in 1998 and 2002. This will have implications for the tourist industry through changing environmental qualities, commercial fisheries through changing fish community structure and abundance, and other activities such as recreational fishing, subsistence gathering and coastal protection. Understanding and planning for this change should be an imperative of governments everywhere. The Great Barrier Reef is no exception.

INTRODUCTION

15. I have been asked by the Queensland Conservation Council Inc (QCC) to provide an expert opinion of the likely ecological impacts of global warming and climate change on the Great Barrier Reef, Australia, by 2050 and beyond. Appendix 1 is a copy of my letter of instructions.

16. This report has been prepared in response to that request for use in an objections hearing concerning a large open-cut coal mine in the Land and Resources Tribunal. The mine is a proposed extension of the Newlands Coal Mine, Wollombi No. 2 Surface Area, at Suttor Creek approximately 129 km west of Mackay, known as the "Newlands Wollombi No. 2 Project" ("the mine").

17. I am instructed that the mine involves 28.5 million tons of black coal being produced over 15 years. The coal from the mine will be transported to domestic and/or export markets for electricity production (thermal or steaming coal) and/or steel production (metallurgical or coking coal). The mining, transport and use of the coal will produce greenhouse gas emissions contributing to global warming and climate change; however, the contribution of these emissions to global warming and climate change is a matter for other witnesses. My evidence concerns the likely impacts of global warming and climate change on the Great Barrier Reef of which the emissions from the mine the subject of this objection are a contributing factor.

18. I note that I have read and understood from the Tribunal's practice direction No. 11 of 2000 that:

    (a) I have overriding duty to assist the Tribunal on matters relevant to my area of expertise;

    (b) I am not an advocate for a party; and

    (c) my paramount duty is to the Tribunal and not to the person retaining me.

19. For the purposes of preparing this affidavit I have been provided with a copy of the objection lodged by QCC 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 on the Great Barrier Reef.

RELEVANT EXPERTISE

20. Appendix 2 to this report is a copy of my resume. My fields of research and professional interest include:

    (a) coral reefs and marine studies;

    (b) the effects of climate change on coral reefs;

    (c) coral bleaching and its connection to global warming; and

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

LIKELY IMPACTS OF CLIMATE CHANGE ON THE GREAT BARRIER REEF

21. In 2004 I co-authored, with my father (Hans Hoegh-Guldberg, an economist), a report entitled, *Great Barrier Reef 2050: Implications of climate change for Australia's Great Barrier Reef* (Hoegh-Guldberg and Hoegh-Guldberg 2004). The report is available in full at http://wwf.org.au/publications/ClimateChangeGBR/ (viewed 12 January 2007). The report is still generally current and I continue to hold the opinions expressed in it. Some of the facts stated in the report can be updated with the further research that has occurred since 2004, but there are no major changes to the facts set out in the report (see also Hoegh-Guldberg 2005). The following paragraphs summarise the scientific evidence and findings contained in the report, updated where necessary, of the likely impacts of global warming and climate change on the Great Barrier Reef.

The scientific evidence of climate change

22. Climate change is one of the greatest challenges facing human populations over the next 100 years. In addition to increases in the overall temperature of the earth, changes are expected in a large range of climate variables including patterns of rainfall and drought, ice volume, ocean temperature, chemistry and sea level. Evidence of rapid changes in these variables is now overwhelming. The role of humans in these changes is equally undeniable scientifically. According to the Intergovernmental Panel on Climate Change (IPCC 2001a) "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities." These changes are bringing and will bring major changes to elements of the biosphere like coral reefs. This section reviews the scientific evidence of climate change and establishes the basis for the four climate change scenarios explored within this report. Within these futures, the possible trajectory of coral reef regions like the Great Barrier Reef will be examined. As was discussed in the introduction to this report, the impact of changes in climate is very dependent on the human context in which is occurs. Information developed in this section is one layer of many and it will be clear that it is the response and actions of people on and around the Great Barrier Reef will be critical in determining the resilience and hence future of this vast ecological resource under increasing levels of climate change.

23. In this section I have relied on the Intergovernmental Panel on Climate Change (IPCC) as the leading international authority on climate change science. In 2001 the IPCC delivered its 3rd major report (IPCC 2001). The IPCC will publish a 4th major report in February 2007 that is expected to largely confirm its earlier projections with narrower bands of uncertainty.

Recent climate change

24. Quite substantial changes have already occurred in the heat trapping behaviour and hence average temperature of the earth. Since the beginning of instrumental records around 1880, global temperature has increased by 0.6 ± 0.2 °C, with the 1990s being the warmest decade (Jones et al. 1999). Within this decade, January-May

1998 was also the warmest period (IPCC 2001, National Climatic Data Center, Asheville, NC) for more than a century (Figure 1).

25. Longer term perspectives on the earth's temperature come from climate proxies. These are records of temperature derived from chemical or physical changes to materials such as coral skeletons, tree rings and ice cores. A range of careful isotopic measurements can yield very accurate records of global temperature. When many sources are compiled, proxy data indicate that global temperature has been relatively stable during the past millennium and that changes over the past 50 years exceed those seen in the past 1000 years. The trajectory in global temperature is 10-50 times steeper over the past 50 years than it has been over any other century in the past 400,000 years.

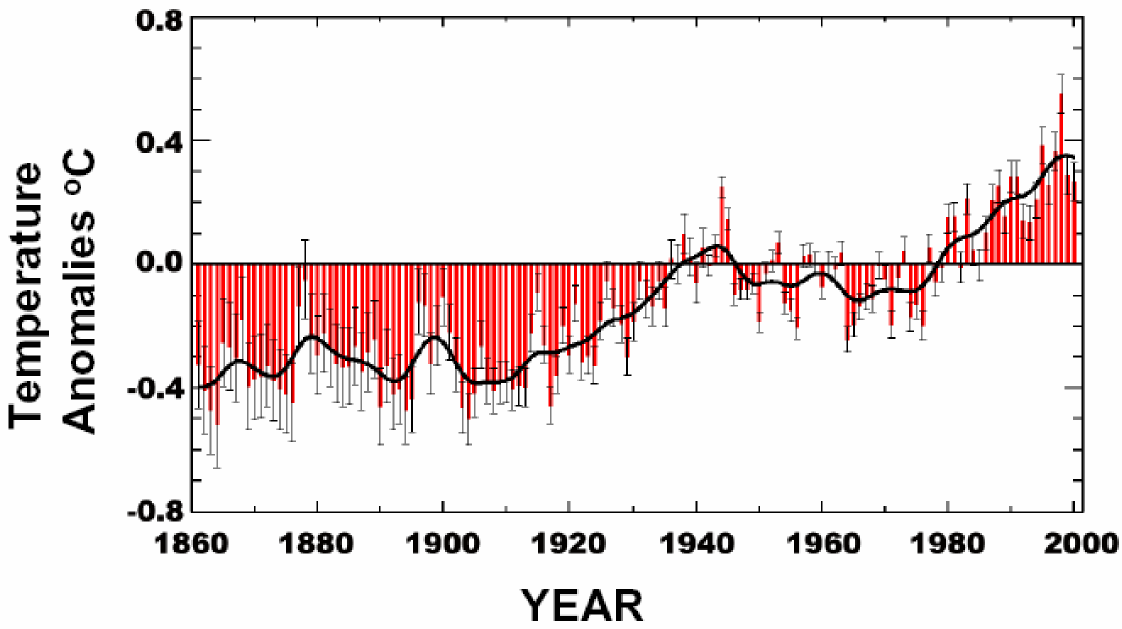

Figure 1: Instrumental records (from thermometers) of global temperature anomalies for the past 140 years (Source IPCC 2001a).

Greenhouse Gases

26. The majority of the recent climate change is associated with changes to the greenhouse gas concentrations in the atmosphere (IPCC 2001a). Greenhouse gases are both natural and human derived elements of the atmosphere that absorb and emit radiation at specific infrared wavelengths (heat) emitted by the Earth's surface. These compounds modify the heat exchange between the earth and its surroundings such that the global temperature is maintained above that of surrounding space (-18°C). This property of the earth's atmosphere is termed the greenhouse effect. Greenhouse gases include carbon dioxide (CO_2), water vapour (H_2O), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3). There are also a number of synthetic fluorine, chlorine and bromine containing compounds that impart a greenhouse effect. Significantly, compounds such as the chlorofluorocarbons (also known for their ability to degrade the earth's ozone shield) are the strongest greenhouse gases on a per molecule basis.

27. Over the past century, the concentrations of greenhouse gases have been changing. This has led to the increased greenhouse effect. Most of this change has been due to

human activities such as the burning of fossil fuels, including coal, the clearing of forests and the increase in agricultural activities. These have lead to changes in the balance of the greenhouse gas constituents in the atmosphere. These trends are currently accelerating.

28. Changes to the function of gas exchange across land, sea and ice interfaces as a result of this warming are also now contributing added influences on the rise of global temperatures. Long-term perspectives on greenhouse gases and global temperature indicate that the two are tightly coupled. Ice cores provide unique data from the entrapped air inclusions that enable direct records of past changes in atmospheric trace-gas composition. A collaborative project between Russia, the United States, and France at the Russian Vostok station in East Antarctica in January 1998 has yielded continuous ice cores of 3,623 m (Petit et al. 1997, 1999). Within the Vostok ice cores, there is a close correlation between Antarctic temperature and atmospheric concentrations of CO_2 (Barnola et al. 1987). Examination of the carbon dioxide concentrations within the core show glacial-interglacial transitions in which atmospheric CO_2 concentrations rose from 180 to 280-300 ppm (Petit et al. 1999).

29. Perhaps the most dramatic conclusion from the Vostok CO_2 record is that present-day CO_2 concentrations (now over 370 ppmv) are unprecedented during the past 420,000 years at least (Figure 2). Concentrations seen in the pre-industrial Holocene (approximately 280 ppmv) can be observed during all interglacials within the past 400,000 years, with the highest values (~300 ppmv) being found approximately 323,000 years ago. Similar statements can be made about temperatures derived from the ice core record. Other ice core data for the past 30,000 - 40,000 years (Delmas et al. 1980; Neftel et al. 1982) show good agreement with the Vostok ice core data.

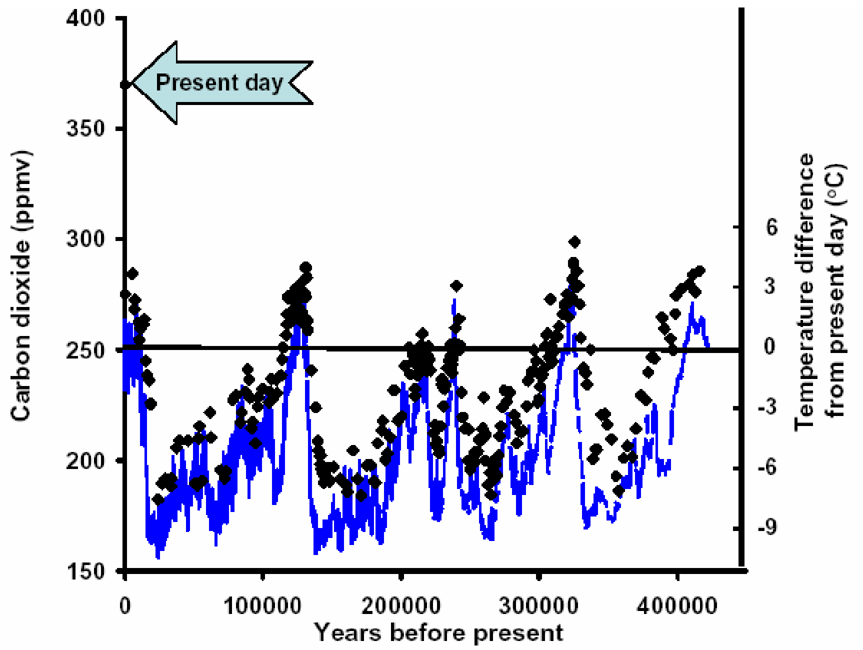

Figure 2: Variation in carbon dioxide (black symbols) and temperature variation relative to today (blue line) in Antarctica from ice core data drilled at the Vostok station. CO_2 data are replotted from Barnola et al. (1999) and temperature data from Petit et al. (1999). Present day carbon dioxide levels are indicated by the arrow.

30. The climate record from the Vostok ice core has now been extended to the past 650,000 years with similar findings from two deep ice cores from in East Antarctica, the deepest coming from Dome Concordia (Dome C) (Siegenthaler *et al*. (2005)). This research indicates that from at least 650,000 years prior to the Industrial Revolution, circa 1750, the concentration of CO_2 in the atmosphere varied between 180 and 280 ppm.

31. While overall global temperatures are increasing, it is salient to note that different parts of the climate system are responding at different rates. For example, polar temperatures are increasing at rates that are faster than in temperate or tropical areas of the planet. Components like the ocean (due to the higher thermal inertia of large volumes of water) are responding at a slower rate within each latitude. In the latter case, these lag times are on the order of 75% that of air temperature responses. This means that a 1°C change in air temperature will be accompanied by a 0.75 °C change in the surface layers (0-100 m) of the ocean.

32. How the climate has changed in the past thousands or millions of years is still an evolving story. There are examples in the past of relatively rapid periods of change (e.g. during shifts between ice age and interglacial periods). While there is evidence for short periods of even higher rates of change in climate, those present in records like the Vostok data tell an interesting story. The most rapid rates of increase in atmospheric carbon dioxide within the Vostok ice core data range from 0.30 to 0.96 ppm per century (Figure 2). The most recent changes (those over the past century) dwarf these (100-200 fold higher) while future rates may be as much as 500 fold higher. Similar conclusions may be drawn from regression data calculated from the temperature data in the Vostok ice core. In this case, the most rapid transitions (seen as the earth came out of glacial periods or ice ages) only range up to 0.2 °C per century. Again recent changes of 0.6 °C over the past century and those projected under even the mildest IPCC scenarios (2.8 °C per century under the A1B scenario or 3.8 °C per century with the A1F1 scenario) are much higher. The observation that changes of a similar absolute magnitude (e.g. 100 ppm) occurred over hundreds of years and not decades, further reinforces this conclusion. Given that these previous periods of change were associated with major changes in regional flora and fauna across the globe, it is highly likely that the earth's biota will respond strongly to current climate change. As will be developed later, the evidence that the earth has already responded to a 0.6 °C over the past century is undeniable (Walther et al. 2002; Parmesan and Yohe 2003).

33. Other aspects of climate have changed as a result of changes in global temperature. This has already had profound effects on organisms that are often restricted by their adaptive capability to survive freezing stress. These matters are addressed in some detail in Hoegh-Guldberg and Hoegh-Guldberg (2004) and I will not address them further here as they are outside the topic that I have been asked to consider for the present hearing before the Tribunal.

Climate change and the ocean

34. Strong physical links exist between ocean temperature and global climates. In a similar way to the atmosphere, the process by which climate change will affect the ocean is highly complex, affecting oceanic circulation and chemistry. Even minor

changes to sea temperature, for example, are likely to result in changes to the currents that flow across the earth's surface. Once changed, currents can affect the flow of heat between regions of the world. In addition to feeding back on terrestrial climate change, changes to current flow and direction can have dramatic influences on local marine conditions with impacts being felt on ecosystems such as coral reefs and temperate kelp forests. There are also a plethora of more subtle influences such as reduced or increased genetic connectivity of marine populations as currents change.

The physical structure of the earth's oceans.

35. Two major transport layers dominate the ocean. Surface waters (100 to 400 m, depending on season and latitude) are made up of low density seawater that is generally warmer, and better mixed, illuminated and oxygenated. These surface waters of the ocean move under the combined influence of wind movements, the Coriolis Effect and the location of landmasses such as continents and islands. Huge gyres in each hemisphere circulate water within each oceanic basin. As a result of the Coriolis effect (inertial forces due to the rotation of the earth), Northern Hemisphere gyres rotate clockwise while those of the Southern hemisphere rotate counter clockwise. At very high latitudes gyres tend to flow in the opposite direction. Smaller currents and eddies form spin off from these main gyres.

36. The surface waters bring heat to higher latitudes. This heat warms higher latitude areas on both land and sea with huge consequences for life at higher latitudes. Without the Gulf Stream, for example, which brings warm water from the south to north Atlantic, the terrestrial and aquatic climates of northern Europe would be significantly colder. This has been proposed as one of the changes that may occur in Europe under climate change (IPCC 2001a).

37. Below the surface layer of the ocean are colder, denser waters that move as function of the thermohaline circulation. The boundary between the two layers of the oceans is defined by a large-scale change in seawater density known as the pycnocline. Thermohaline circulation involves a massive, long-lived flow of water from low to high latitude and from deep to shallow and back again. The thermohaline circulation is driven by the temperature differential between equatorial and polar locations. This force leads to a rapid cooling and eventual sinking (due to increasing density) of warm saline water originating from lower latitudes. As a result of water sinking at the poles, a "conveyor belt" like system operates in which deep waters move toward the equator while the surface components of the thermohaline circulation move polewards. The residence time of deep water can be as long as 200-500 years for the Atlantic Ocean and 1,000-2,000 years for the Pacific Ocean.

Recent changes

38. Climate change is having a major impact on three fundamental variables associated with oceanic environments. These are the temperature, calcium carbonate saturation state and the sea level. While each variable is likely to have different overall impacts on life in the ocean, the combination of all three changes is expected to have a major impact on the distribution and abundance of marine organisms.

a. Calcium carbonate saturation state

39. When carbon dioxide is present above a solution, carbonic acid forms as carbon dioxide interacts with the water molecule. As a result, the concentration of critical ions such as carbonate (which is important for calcification) decreases in concentration. The net effect of this is that the carbonate alkalinity of seawater (a measure of the availability of carbonate ions) will decrease as carbon dioxide within the earth's atmosphere increases (Gattuso et al. 1998, Kleypas et al. 1999).

b. Sea level

40. Sea level was 120 m below where it is today during the last ice age. Over the past 100,000 years, sea level has fluctuated significantly as temperature has modified the volume of the ocean and affected the storage of ice in glaciers and at the poles. During the transition out of this period of glaciation, sea level changed at an average rate of 10 mm/yr (rates were as high as 40 mm/yr at some times). During the interglacial, rates of sea level rise have been much slower (0.1 to 0.2 mm/yr over the last 3,000 years; Church et al, 2001). Not surprisingly, changes in sea level have had major impacts on the abundance and particularly the distribution of both marine organisms and ecosystems.

41. There is a growing consensus that the mean global rate of sea level rise during the 20^{th} century has been nearly 2 mm/yr, which is 10-fold higher than the average of the past several millennia. These data have been generated from tide gauge data taken since the late 19th century, historical land records, and geological evidence from the late Holocene period (Douglas et al. 2002).

c. Sea temperature increase

42. Ocean temperature is responding rapidly to heating of the earth's atmosphere. The heat content of the global ocean has increased 2.3×10^{23} joules between the mid-1950s and mid-1990s, which represents a volume mean warming of 0.06 °C. This increase in heat content of the ocean has not been distributed evenly. Substantial increases have occurred in the upper layers of the ocean, with the mean temperature increase for the upper 300 m of the global ocean over the same three decades being 0.31 °C (Levitus *et al.* 2000). Deep oceanic warming is also occurring and rates also vary strongly with latitudes (Barnett et al. 2001, Gille 2002).

43. Changes in global temperatures can directly affect the rates and directions of ocean water movement. Most global circulation models indicate that the thermohaline circulation of the planet, for example, is likely to weaken as greenhouse warming continues. Dickson *et al* (2002) produce convincing evidence of a rapid and sustained freshening (decreased salinity) of the deep Atlantic Ocean. Though these changes may appear small (0.03 ppm salinity change over the past 40 years), they indicate that major changes may be in store for the heat budget and functioning of the earth's oceans. As the "conveyor belt" is critical for both terrestrial and marine environments, changes to this critical oceanic system are being monitored with increasing interest by those interested in future climate trajectories.

44. The El Niño Southern Oscillation (ENSO) is a major determinant of both terrestrial and marine climates in the southern hemisphere. Important aspects such as coral

bleaching are triggered by ENSO events. Some changes in ENSO over the past 100 years appear to have occurred with events becoming stronger and more frequent. Complete consensus is missing at this point however. Recent ENSO events (over the 20th century) appear also to have been strong compared with ENSOs of previous cool (glacial) and warm (interglacial) periods (Tudhope et al. 2001).

Future climate change

45. Anthropogenic activities such as clearing forests and burning fossil fuels are changing the composition of the atmosphere and climate (IPCC 2001a). The big question is how the magnitude and rate of climate change will vary over this century. Future changes in climate are to some extent already determined due to the long residence times of gases in the atmosphere. Effects of past emissions may last for hundreds of years. In the case of CO_2, effective residence times (time for removal of 63% of the anthropogenic excess of a greenhouse constituent in the atmosphere if anthropogenic production falls to zero) are of the order of approximately 230 years or more (Fuglestvedt et al. 2001). This essentially means that activities from 100-200 years ago are still major determinants of today's atmosphere. Many other greenhouse constituents have shorter residence times. Methane (CH_4) has an estimated mean residence time of 10 years (Prather, 1996, 1998); Nitrous oxide (N_2O) 100 years, (Prather, 1996, 1998), and the chlorinated fluorocarbons, CFC-11 and CFC-12, 50 and 102 years respectively (Prather et al., 1995). How residence times vary between atmospheric components depends on the complex relationships between concentrations and the many sources and sinks that exist for each component.

46. Projections of future conditions on the planet are based on complex mathematical models (general circulation models or GCMs) that simulate future additions and removals of greenhouse gasses and the resulting heat trapping behaviour of the atmosphere. They also increasingly take into account behaviour and interaction of components of the climate system. Greenhouse gas concentrations and climate change projected by these models are subject to large uncertainties in the effects of both natural processes and human activities. This has lead to scenario building exercises that take into account different sets of conditions and assumptions. The Intergovernmental Panel on Climate Change has extensively reviewed the outputs of the major GCMs for 40 quantitative scenario variations as part of its Special Report on Emission Scenarios (IPCC 2000).

47. The results of considering both natural and anthropogenic forces plus different social and political futures give a full range of scenarios or possibilities that have been published in the recent IPCC Third Assessment report (IPCC 2001a). These give a range of future global responses that include ranges of 2-3 fold increases in GHG concentrations, a 1.4 to 5.8°C and 0.3 to 0.5 m increases in temperature and sea level by 2100 respectively (IPCC 2001a).

Projected changes in the ocean

48. As with terrestrial climates, changes to atmospheric composition and global temperature will also change conditions in the ocean. The principal changes are associated with the following three variables.

a. Calcium carbonate saturation state

49. Gattuso et al. (1998) and Kleypas et al (1999) demonstrate that doubling carbon dioxide concentrations in the atmosphere will decrease the aragonite saturation state in the tropics by 30 percent by 2050 (under a doubling of carbon dioxide). A decrease in calcification rate of similar magnitude (25%, range 11-40%, Langdon 2000) as a result of reduced carbonate saturation state (under CO2 doubling) has now been shown in a variety of corals and other marine animals and plants. Greenhouse emission scenarios that produce even greater changes to atmospheric carbon dioxide will lead to even greater decreases in the ease with which calcifying organisms and processes can precipitate calcium carbonate.

b. Sea level

50. Global sea level will increase as planetary temperatures rise mainly due to the thermal expansion of ocean water (responsible for about 70% of the increase), the melting of glaciers and changes to the volume of Arctic and Antarctic ice sheets. The expected increase in sea level is approximately 9-29 cm over the next 40 years, and 28-98 cm by 2090 (Church et al 2001, IPCC 2001a). These changes have major ramifications for human infrastructure in coastal areas. A 25 cm rise, for example, would displace most people from the delta regions of major rivers such as the Nile, Ganges and Yangtze as well drowning Pacific and Indian Ocean nations such as the Maldives, Kiribati and Tuvalu (Church et al. 2001).

51. In concert with the direct effects of coastal inundation are the impacts of storm surge (Nichols et al. 1999). Impacts on marine ecosystems will vary according to the proximity to coastlines, in some cases only minor changes are likely while in others major impacts are likely. According to Nichols et al. (1999), sea-level rise could cause the loss of up to 22% of the world's coastal wetlands by 2080. Combined with other human impacts, this number is likely to climb to a loss of 70% of the world's coastal wetlands by the end of this century.

c. Sea temperature

52. The increase in temperature of the surface layers of the ocean has been observed to lag by 75% when compared to increases in global temperature. The expected change in sea temperature by 2100 is, therefore, considered likely to be in the realm of 1.5-4.5°C with the increase continuing for several centuries there after at a slow rate (IPCC 2001a).

53. Whether or not sea temperatures in the tropics will reach a ceiling of 32°C is still a matter of debate. Also important to local marine temperatures are changes to the strength and direction of oceanic currents. By the far the greatest natural disturbance has been associated with the El Niño Southern Oscillation (ENSO). The functioning of this weather system affects many of the currents throughout the world. Changes in the functioning of climate systems like ENSO have also been projected to occur under climate change by many greenhouse gas driven global circulation models. GCM runs done with the Max Planck model, ECHAM4, simulate ENSO with a high degree of realism (Timmermann et al. 1999) and show more frequent El Nino conditions and stronger cold events occur in the tropical Pacific Ocean as greenhouse-gas concentrations are increased.

Conclusions

54. The greenhouse gas composition of the earth's atmosphere has changed more rapidly than any change recorded within the last half a million years. We are currently experiencing concentrations of carbon dioxide that have not been seen in this same period. Past changes in greenhouse gas concentrations have been matched by corresponding changes in global temperature. Global temperatures have increased by 0.6°C since 1880, and are continuing to rise rapidly. Based on a large number of general circulation models, the Intergovernmental Panel on Climate Change (IPCC) projects increases in atmospheric carbon dioxide and temperature that range between 100 to 650 ppm and 1.5 to 6°C respectively. These changes in the terrestrial setting are expected to increase the number of climate extremes relative to 1990, change patterns of rainfall and affect evaporation rates.

55. Similar large-scale changes are likely in aquatic environments. Sea temperature and level, current velocity and direction, as well as calcium carbonate alkalinity are all expected to change markedly. It is important to realize that the degree of change under different scenarios will be indistinguishable over the short-term (20-40 years) but will differentiate into low and high rates depending on actions that are taken over the next few decades. If, for example, greenhouse gas emission rates are reduced dramatically as fossil fuels are phased out and energy efficiency increased, final concentrations of carbon dioxide may be as low as 450 ppm and sea warmer by only 2°C. If, on the other hand, business as usual dominates, carbon dioxide concentrations may stabilize at 1000 ppm and our seas warm (eventually) by as much as 6°C. While change is inevitable given the long residence times of carbon dioxide and other greenhouse gases in the atmosphere, the course of action over the next decade will be critical in determining the amount of change that will occur in the earth's ecosystems.

Impacts on ecosystems

56. The organisms that make up the rich life forms of the earth are finely tuned to the physical and chemical makeup of their environment. This is primarily due to the relative stability of environmental conditions over thousands of years. Not surprisingly, changes to the mean or range of these conditions can have substantial effects on populations, communities and ecosystems. These responses may be mild, as organisms adjust their physiological processes to the new conditions (acclimation) or acute, as organisms sicken or experience higher mortality rates as their thresholds for particular conditions are exceeded. The latter may result in a shift in the genetic structure (adaptation) and/or geographic range of a population (range shift). In all of these observations, there is an important interplay between the rate of change of the environment and the rate at which the genetic structure and tolerance of organisms can vary.

57. Substantial changes have already occurred in both terrestrial and marine ecosystems with only a 0.6°C change in global temperature (review: Walther et al. 2002). These past changes give us some insight into what might happen as the earth continues to warm. Given the size of the change expected under even the most minimal greenhouse scenario (an increase in 2°C by 2100), however, it must be kept in mind that future changes can only be partially understood in the context of changes that have occurred over the past century.

58. Most of the impact due to climate change detected so far can be grouped according to changes in the timing of biological events (phenology), changes to the distribution and abundance (including range shifts) and changing community complexity and dynamics.

59. Hoegh-Guldberg and Hoegh-Guldberg (2004) reviewed the phonological shifts, range shifts and changes in community dynamics for terrestrial and marine ecosystems generally. Here I will only deal with the impacts on coral reefs and the Great Barrier Reef in particular.

Impacts on Coral Reefs

60. Coral reefs are the most diverse marine ecosystems on the planet and have a central importance to the tropical coastlines. Complex and productive, coral reefs more biodiverse than any other marine ecosystem. In addition to this, coral reefs provide critical support for at least 100 million people across the planet (Bryant et al. 1998). Unfortunately, recent evidence suggests that coral reefs are also very sensitive to environmental changes like climate change (Hoegh-Guldberg 1999). In the words of Klaus Toepfer, the United Nations Environment Programme Executive Director, "Coral reefs may be the ecosystem equivalent of the canary in the coal mine, giving early warning that the world's ecosystems can no longer cope with growing human impacts." (UNEP 2000). The canary analogy is apt, although to lose a canary of such importance begs the question as to whether coral reefs really are the canary or, to keep within the analogy, "half the mining team".

61. This section outlines the importance and threats that face coral reefs across the planet. Reviewing this information is central to placing the health and importance of the Great Barrier Reef within the global context. The Great Barrier Reef is currently among the healthiest and best managed coral reef ecosystems in the world. Despite this, it is threatened by a number of direct and indirect human activities. As we shall see, coral reefs are in very poor shape worldwide. According to the authors of the Global Coral Reef Monitoring Network, an estimated 40% of the world's coral reefs will be lost by 2010, and another 20% in the 20 years following unless urgent management action is implemented (Wilkinson 2000). The combination of climate change amid an intense setting of other impacts and stresses has reduced the resilience of reef systems to a point where most are threatened by elimination. The Townsville Declaration on Coral Reef Research and Management (Hughes et al. 2002, 2003; Pockley 2003) highlights the near unanimous opinion of the world's leading scientists that the coral reefs are globally and critically endangered.

The current state of coral reefs

62. Coral reefs supply food and resources (e.g. limestone building materials) to communities that often live immediately adjacent to coral reefs. They play critically important roles as sources of income and resources through fishing, tourism, building materials, coastal protection and biodiscovery (Carte 1996). Approximately 15% of the world's population (approximately 0.5 billion people) live within 100 km of coral reef ecosystems (Pomerance 1999). The majority of human communities living along coral coastlines are economically poor and directly depend on coral reefs for their survival through subsistence foraging

(Bryant el al. 1998). The value of this type of support is hard to estimate economically but runs into the tens of billion of dollars each year (Bryant et al. 1999).

63. In addition to direct support to subsistence fishers, commercial fishing in the rich waters of coral reefs generates at least 6 million metric tons of fish catches globally on an annual basis (Munro, 1996). This income is important to both developing and developed countries.

64. The extraordinarily high biodiversity of coral reefs is inherently difficult to value formally. The sheer scale of the coral reef biodiversity, with its hundreds of thousands of unexplored gene pools, perhaps negates the need to calculate this formally. About 100,000 species have been described from the world's 375,000 km^2 of coral reef. This is a tiny fraction of an estimated 0.5 to 2.0 million species that live on coral reefs (Spalding et al. 2002). Other estimates range as high as 9 million species being associated with coral reefs (Bryant et al. 1998). This biodiversity has an increasing value as a storehouse of potential novel compounds. Recent advances in the molecular sciences (e.g. robotic sequencing and screening, microarrays and molecular databases) are making gene and pharmaceutical discovery many hundreds of times faster than it was even a decade ago. Excellent prospects exist for the discovery of new medicines, chemicals and materials from these vast ecosystems. Economic wealth is being built upon these discoveries (e.g. conotoxins from *Conus* sp., Dutton et al. 2002; pocilloporin from reef cnidarians, Dove et al. 2001; anticancer drugs from sponges Wallace 1997). While this exploration in its infancy, it is significant to note half of the potential pharmaceuticals being explored at present are from the oceans, and many of these are from coral reef ecosystems.

65. Coral reefs may be even more valuable in ways that are often unappreciated. By breaking the force of oceanic waves, corals reefs provide protection along tropical coastlines all over the planet (including the Caribbean as quoted above from Dixon et al. 2001). This protection is critical for coastal cities and towns, and for other ecosystems such as sea grass and mangrove communities that require calm waters in which to grow and proliferate. While these ecosystems have inherent tourist and biodiversity value, their value as critical nursery grounds within the network of coastal habitats is enormous. Many commercially important species spend their early life history stages in these rich habitats.

Reef-building corals: the framework builders of coral reefs

66. Coral reefs flourish in warm shallow seas. Their abundance varies as a function of latitude with the greatest abundance of corals being located closest to the equator. Light, temperature and the carbonate alkalinity of seawater decrease in a poleward direction, making the formation of carbonate reefs more difficult at higher latitudes (Kleypas et al. 1999a). In many ways, the productivity and biodiversity of coral reefs is at odds with the nutrient depleted waters of the earth's tropical oceans. Starting with Charles Darwin, visitors to coral reefs have marvelled at how these productive ecosystems exist in waters that otherwise support only the lowest phytoplankton populations (Darwin 1842, Odum and Odum 1955). Coral reefs can support (or did in the past, see Jackson et al. 2001) massive populations of fish, birds, turtles and marine mammals (eg, Maragos, 1994; Kepler et al, 1994). Akin to

the cactus gardens of tropical nutrient deserts, coral reefs tightly recycle nutrients between often closely associated mutualistic partners. This has been identified as the feature for why coral reefs are so diverse in this otherwise desolate setting of tropical oceans (Muscatine and Porter 1977, Hatcher 1988).

67. Reef building corals build the framework of coral reefs through their calcareous exoskeletons that may remain long after the animal-plant tissue has been removed. These skeletons are in turn cemented together via the combined activity of calcareous algae and simple sedimentary infilling and consolidation. The resulting structure becomes the habitat for thousands of species of animals, plants, fungi and protists. While approximately 93,000 species have been described from the world's coral reefs, estimates of potentially undescribed species range from 948,000 to up to 9 million (Reaka-Kudla 1996).

68. Reef-building corals live in a mutualistic symbiosis with single celled dinoflagellate algae known as zooxanthellae (Trench 1979). These tiny plants live inside the cells of the coral host and continue to photosynthesize in the light as they would if they were free-living. Instead of retaining the sugars and amino acids that result from this activity for their own growth and reproduction, zooxanthellae export more than 95% of their photosynthetic production to the coral host (Muscatine 1967; Muscatine 1990). In return, zooxanthellae have direct access to the waste products of animal metabolism (fertilizer), which are lacking in the surrounding waters. The close association of animal (heterotroph) and plant (phototroph) avoids the problem of inorganic nutrients and food substrates becoming diluted within the vast nutrient poor waters of the tropics. The success of coral reefs in the otherwise nutrient deserts of tropical oceans is seen as a direct consequence of the mutualism exemplified by corals and their zooxanthellae (Muscatine and Porter 1977).

69. Some studies suggest that genetic diversity within coral symbionts may be a strong foundation for adaptation of corals to rising temperatures, although the weight of evidence suggests the opposite. Until 1980, all reef-building corals were thought to contain a single species of symbiotic dinoflagellate called *Symbiodinium microadriaticum* (Freudenthal 1962; Taylor 1983). Starting with Robert Trench and associates at the University of California at Santa Barbara (Trench 1979; Schoenberg and Trench 1980a, 1980b), however, results accumulated to reveal that zooxanthellae in reef-building corals are a collection of many taxa (Rowan et al. 1997; Loh et al. 1997). A recent survey of the molecular identity of symbionts from 86 host species from the Great Barrier Reef representing 2 genera from Class Hydrozoa, 6 genera from Subclass Alcyonacea, and 32 genera from Subclass Zoantharia (28 scleractinian, 1 actiniarian, 2 zoanthidean, and 1 corralimorpharian) found 23 distinct types of zooxanthellae (LaJeunesse et al 2003). Many hosts have 2 or more genetic varieties of zooxanthellae in their tissues. The meaning of the large molecular diversity of symbionts in corals is an area of active research. While some molecular differences appear to be associated with distinct physiological behaviours (Rowan et al. 1997; Rowan 1998), it is not a foregone conclusion that molecular differences always correlate with physiological differences (Hoegh-Guldberg et al. 2002). This will be discussed further in the section on adaptation and physiological tolerances.

Human impacts on coral reefs

70. Coral reefs have persisted for almost 200 million years even after brief absences following global calamities such as the asteroid strike at the Cretaceous Boundary. They show enormous resilience in geological time (i.e. over millions to tens of millions of years). Paradoxically then, coral reefs appear to be highly sensitive to the increased direct and indirect pressures from human activity. This sensitivity was recently highlighted in the Townsville Declaration on Coral Reef Research and Management (Pockley 2003; Hughes et al. 2002; Hughes et al. 2003) which concluded "Overfishing and pollution have driven massive and accelerating decreases in abundance of coral reef species and have caused global changes in reef ecosystems over the last two centuries. If these trends continue, coral reefs will decline further, resulting in the loss of biodiversity and economic value." According to some estimates, almost a million species are likely to face extinction before 2040 (Reaka-Kudla 1996).

71. The effect of human population growth in tropical oceans can only be described as an onslaught of destructive activity. Jackson et al. (2001) demonstrate from paleological, archaeological, and historic data that a range of disturbances including overfishing and coastal development, have consistently led to major changes in ecosystem structure and health. In many ways, the processes involved are subtle. Hughes (1994) illustrated major changes that are wrought when herbivores are consistently removed by fishing to the point where reef resilience was lost and a permanent phase shift to algal dominated communities occurred. Coral communities around the island of Jamaica used to have (prior to 1977) coral cover in excess of 70%. It is currently below 5% in most places. Several natural factors interacted with anthropogenic stresses to produce this outcome. Firstly, Hurricane Allen reduced coral cover to 22-38% (from 47% to 70%, Hughes 1994). Secondly, the sudden loss of the black sea urchin, *Diadema antillarum*, due to a virus between 1982 and 1984 led to a loss of critical herbivore control of algal growth. As a result, coral settlement and growth was inhibited and coral cover dramatically declined. The problem was that fish grazers had been eliminated in the 100 year period prior to 1980 – leaving *D. antillarum* as the principal grazer. With no other grazer to take the place of *Diadema*, macroalgae (seaweeds) out-competed corals for space on the reefs along the coast of Jamaica and eventually dominating the substrate. In short, the removal of large herbivorous fish from the ecosystem led to a decline in the resilience (i.e. ability to recover from a disturbance) of the reef system (McClanahan et al. 2003; Pockley 2003). This type of circumstances has been repeated in many parts of the world as key elements like grazing fishes have been removed from coral reefs and has resulted in ecosystems that, by being thrown out of balance, do not have the complex characteristics required for resilience (Folke 2003).

72. In addition to over-exploitation of reef species, coral reefs have been impacted by a range of other human activities. Global climate change is compounding the effect of these other pressures such as coastal development, destructive fishing, agricultural run-off, and marine based pollution. They will be discussed in further detail in relation to the risks that they represent in terms of compounding the effects of climate change.

Coral bleaching and climate change

73. The algal symbionts of reef-building corals exist at high densities within the host tissues. The population densities of symbionts range from between 0.5 to 5 x 10^6 cells cm^{-2} of host surface under normal conditions (Drew 1972) with low rates of migration or expulsion to the water column (Hoegh-Guldberg et al. 1987). Over time, symbiotic dinoflagellate populations vary slowly in response to seasonal changes in environmental conditions (Jones 1995; Fagoonee et al. 1999; Fitt et al. 2000). These changes probably represent slow adjustments of symbioses that optimize the physiological performance of the coral-algal symbiosis as the environment changes.

74. Under a variety of stresses, abrupt changes to the density of zooxanthellae in symbiotic corals and other invertebrate hosts can occur (Brown and Howard 1985; Hoegh-Guldberg and Smith 1989; Hoegh-Guldberg 1999). These stresses include changes to salinity (Goreau 1964; Egana and DiSalvo 1982), light (Vaughan 1914; Yonge and Nichols 1931; Hoegh-Guldberg and Smith 1989; Gleason and Wellington 1993; Lesser et al. 1990), toxin concentrations (e.g. cyanide, Jones and Hoegh-Guldberg 1999; copper ions Jones 1997), microbial infection (e.g. *Vibrio*, Kushmaro et al. 1996) or temperature (Jokiel and Coles 1977, 1990; Coles and Jokiel 1978; Hoegh-Guldberg and Smith 1989; Glynn and D'Croz 1990). This phenomenon has been referred to as 'bleaching' due to the fact that corals rapidly lose brown colour (due to the zooxanthellae) and turn a brilliant white.

75. Bleaching at small local scales (10-1000 m^2) has been reported for almost a century (Yonge and Nichols 1931). Bleaching at larger geographical scales, however, is a relative new phenomenon. Prior to 1979, there are no formal reports of mass coral bleaching in the scientific literature. Since that date, however, the number of reports has risen dramatically. Mass bleaching events have a number of possible outcomes. In mild cases, reefs will recover their colour within months. At the other end of the spectrum, mass bleaching events led to large proportions of coral communities dying. In 1998, for example, coral reefs off the Australian coastline recovered from widespread bleaching with minimal loss of reef-building coral (Berkelmans and Oliver 1999). However, in the Indian Ocean, Palau, Okinawa and North West Australia, coral communities lost up to 95% of their coral cover in the same year

76. While localized bleaching can arise as a result of any number of stresses, mass coral bleaching is tightly correlated with short excursions of sea temperature above summer maxima. Over the past 20 years, there have been six major global cycles of coral bleaching ("mass coral bleaching events"). A combination of elevated sea temperature and exposure time predicts mass coral bleaching with great certainty (Strong et al. 1996, Hoegh-Guldberg 1999, Strong et al. 2000, Hoegh-Guldberg 2001). This highlights the existence of a thermal threshold values. These vary with latitude, species, clone, other physical factors (e.g. light) and history (Edmunds 1994, Jones et al. 1998, Hoegh-Guldberg 1999, Berkelmans and Willis 1999, Brown et al. 2002). Despite this secondary source of variability, satellite measurements of sea surface temperature anomalies can be used to predict bleaching events several weeks in advance with more than 90% accuracy (review: Hoegh-Guldberg 1999). Sea surface temperature measurements also appear to deliver information on the intensity and outcome of bleaching events. While some fine tuning needs to be done with regard to the influence of other factors (e.g.

Brown et al. 1999, Mumby et al. 2001, Berkelmans and Willis 1999), the relationship between sea surface temperature anomalies, exposure time and coral bleaching and mortality gives strong indications of what the progression will be from bleaching to mortality as heat stress increases over the next century. A doubling of CO_2 will lead to degree heating months (DHM) for most tropical regions that will be greater than threefold higher than those which caused large scale mortality events in Palau, Okinawa, Seychelles and Scott Reef (Hoegh-Guldberg 2001).

Heat stress and mechanisms of coral bleaching

77. There is a considerable set of information now on why corals and their zooxanthellae bleach. Coles and Jokiel (1977) were among the first researchers to investigate heat stress in reef-building corals during a project looking at the effect of heat effluent flowing from a power plant in Kaneohe Bay in Hawaii. Coles and Jokiel (1977) noted that corals that were warmer than normal were bleached. Those that were warmest were dead. In their investigation of the physiology of heat stressed corals, they noted the rapid reduction in photosynthetic activity early in the syndrome. Some of this decrease was due to reduced zooxanthellae numbers as the corals bleached. However, subsequent work has revealed that photosynthetic decreases occur prior to the onset of the loss of zooxanthellae (Hoegh-Guldberg and Smith 1989; Iglesias-Prieto et al. 1992; Fitt and Warner 1995; Iglesias-Prieto 1995; Warner et al. 1996; Jones et al. 1998). Heat stressed corals develop an increased susceptibility to the phenomenon of photoinhibition, which is very similar to the mechanisms that are faced by all plants when they become temperature stressed. This mechanism, in which light becomes a liability, also explains the important role that lights plays as a secondary factor (Jones et al. 1998, Hoegh-Guldberg 1999).

78. A key observation regarding heat stress in reef-building corals is that not all corals are equally sensitive to temperature. Corals with thicker tissues and more massive growth forms (e.g. *Porites* spp., *Goniopora* spp., *Montipora* spp.) tend to be more tolerant than corals that have thinner tissues (e.g. *Acropora* spp., *Stylophora* spp., *Pocillopora* spp.). Some species of zooxanthellae may also be more thermally tolerant although the evidence is equivocal at this point (Hoegh-Guldberg 1999). The thermal threshold above which corals and their symbionts will experience heat stress and bleaching also varies geographically, indicating that corals and zooxanthellae have evolved over evolutionary time to local temperature regimes (Coles et al. 1976, Hoegh-Guldberg 1999). Corals closer to the equator have thermal thresholds for bleaching that may be as high as 31°C while those at higher latitudes may bleach at temperatures as low as 26°C. Thresholds may also vary seasonally. Berkelmans and Willis (1999) revealed that the winter maximum upper thermal limit for the ubiquitous coral *Pocillopora damicornis* was 1°C lower than the threshold for the same species of coral in summer. These shifts are evidence of thermal acclimation, a physiological adjustment that can occur in most organisms up to some upper or lower thermal limit.

79. Why corals sit so close to their thermal threshold for bleaching is of great interest, especially in the context of rising sea temperatures. The explanation is also important to perspectives as to why mass bleaching events appear to be becoming more frequent and intense. Several factors are involved in the latter. The first factor involved is the increase in tropical/subtropical sea temperatures over the past 100

years. Tropical and subtropical oceans are about 0.4 – 1.0°C warmer than they were 100 years ago (Hoegh-Guldberg 1999, Lough 2000). The second factor is associated with the timing and intensity of El Niño Southern Oscillation (ENSO) events (Glynn 1988, 1991, 1993, Hoegh-Guldberg 1999). The effect of these events is that they combine to produce short periods during the summer months in which sea temperatures rise above the thermal tolerance of reef-building corals and their zooxanthellae. The last factor is the apparent stability of the thermal threshold of corals. It appears that rates of adaptation to changing conditions over the past 30 years are much slower than the rate of increase at which thermal stress has increased on coral reefs. This will be discussed further below as it is critical to later efforts to build scenarios of how coral reefs like the Great Barrier Reef will look later this century.

Mortality estimates of reef-building corals following bleaching

80. As discussed above, mortality following mass bleaching ranges from zero in cases of mild bleaching (e.g. Harriott 1985) to close to 100% as seen at many sites in recent global events (Wilkinson 1999). The Global Coral Reef Monitoring Network (supported by more than 30 countries, IOC-UNESCO, UNEP, IUCN and the World Bank) has produced a series of annual reports on the state of coral reefs since the mid 1990s (Wilkinson 2002; Wilkinson 2004). These reports, though of varying qualities, are an attempt to get a yearly snapshot of coral reef health across the planet. The numbers from 1997 to 1998 indicate the scale of mortality that can occur in a global cycle of mass coral bleaching. Prior to 1998, the GCRMN surveys reported a loss of 9.5% of living corals from 6 regions. During 1998, one of the warmest years on record, regions lost an average of 17.7% of their living reef-building corals. The range of mortality estimates is perhaps the most interesting detail hidden within the average. While some regions (e.g. Australia and Papua New Guinea) lost an estimated 3%, regions like Arabian Gulf and Wider Indian Ocean lost 33% and 46% respectively during the single event in 1998.

81. The novelty of recent changes on coral reefs is an important part of understanding global events. Several studies have looked into the past behaviour of reefs and have come up with some compelling data that indicate that recent mass mortalities of the 1990s have not been seen for at least the last 3,000 years. *Acropora cervicornis* for example, was a dominant species across the central shelf lagoon of Belize up until 20 years ago. In the 1980s, however, disease (white band disease) resulted in the complete mortality of *A. cervicornis*. Stands of the foliose (scroll-like) coral *Agaricia tenuifolia* quickly replaced *A. cervicornis* in the early 1990s but were wiped out by the high water temperatures of 1998. The mortality of *A. cervicornis* in the 1990s left an unambiguous layer of coral branches in the sediments of reefs throughout the Caribbean. Investigation of reef deposits reveals that the scale of these mortality events appears to have been unique in the past 3000 (Aronson et al. 2002). Aronson and his colleagues analysed 38 cores from across the 375 km2 central lagoon basin and could not demonstrate any similar layer in sediments stretching back at least as far as 3000 years ago.

Sublethal impacts of thermal stress

82. Often forgotten from the discussion of impacts of climate change on coral reefs are the sub-lethal or chronic effects of thermal stress that may or may not be associated

with bleaching and/or death. These may be as important as changes in mortality schedule and have the potential to bring about large changes in growth, calcification and age structure. These in turn can fundamentally affect reef function, resilience and survival. Reef-building corals that experience thermal stress have reduced growth, calcification and repair capabilities (Goreau and Macfarlane 1990; Glynn 1993; Meesters and Bak 1993). Not surprisingly, as thermal stress reduces the amount of photosynthetic activity and as zooxanthellae are lost from reef-building corals, the amount of energy available for these fundamental processes is reduced. In addition to this, the amount of energy available for reproduction is also potentially compromised under thermal stress. Coral species utilise a variety of reproductive modes including brooding of larvae and broadcast spawning of gametes for external fertilisation. Coral reproduction is generally sensitive to stress (Harrison and Wallace 1990) and measures of reproductive output or fecundity can be used as indicators of reactions to various stressors such as mechanical damage (Ward 1995), nutrients (Tomascik and Sander 1987, Ward and Harrison 1997, Ward and Harrison 2000) and oil (Guzman and Holst 1993).

83. Mass coral bleaching has been reported to affect coral reproduction. Szmant and Gassman (1990) examined a limited number of corals (due to marine park restrictions) following a bleaching event in Florida in 1987 and found that bleached colonies did not complete gametogenesis in the season following the bleaching event. They also found that bleached colonies had 30% less tissue carbon and 44% less tissue nitrogen biomass per skeletal surface area than unbleached colonies. Ward et al. (2001) demonstrated a failure of gametogenesis in a large number of corals that were affected in the southern Great Barrier Reef by the 1998 mass bleaching event. This is similar to observations made for soft corals by Michalek-Wagner and Willis (2000). Ward et al. (2001) also demonstrated that fertilization, settlement and juvenile growth were all compromised at the end of 1998, even though the bleaching event occurred in March of that year. The implications for reef dynamics are considerable as recovery of affected reefs can be heavily dependent on larval recruitment. There is growing evidence that low levels of larval recruitment follow periods of thermal stress on coral populations. For example, severe bleaching also occurred on the West Australian coast in 1998 and was followed by a year of failed recruitment at Scott Reef (L. Smith, Australian Institute of Marine Science, pers. comm.).

Climate change and future coral bleaching and mortality

84. The conditions under which coral reefs have prospered are changing rapidly. Global temperatures and carbon dioxide concentrations are now higher than they have been for at least the last 650,000 years. There is now very strong evidence that coral reefs have already experienced major impacts from climate change. Tropical oceans are 0.5-1.0°C warmer than they were 100 years ago (Lough 1999). Current projections of changes to the earth's climate suggest that sea temperatures may be 2-5°C higher by 2100 than they are currently. Some studies suggest that reefs will not be coral dominated by the middle of the current century (Hoegh-Guldberg 1999, 2001). The implications of these types of scenarios for tropical near shore communities and the humans that interact with them are enormous and must be considered in any serious exercise to plan the future.

85. Even under mild climate change scenarios, coral reefs will undergo major increases in coral bleaching and mortality. Drawing together the responses of reef-building corals to ENSO related excursions in sea temperature over the past 20 years, Hoegh-Guldberg (1999) derived a series of simple thermal thresholds for a series of sites and compared these threshold values to future sea temperatures. As discussed previously, some variation surrounds thermal thresholds due to the influence of other secondary factors (e.g. light, history, exposure time) and the species of coral involved. However, despite the influence of these secondary factors, thermal thresholds can be used to predict bleaching events from satellite measurements of sea surface temperature. There is a threshold above which all corals will bleaching and/or die (as happened in many sites in the 1998 global event). Consequently, sea temperature is a fairly good indicator of whether a reef will bleach or not for exposure times of 3-4 weeks (Hoegh-Guldberg 1999). Estimates of past and future sea temperatures were generated by a range of General Circulation Models areas of tropical ocean and compared to these threshold values. This analysis was repeated for several models with and without the influence of such factors as aerosol cooling.

86. The results of this analysis were quite dramatic. In every model run attempted, sea temperatures rose over the early part of the 21st century such that they exceeded the threshold for bleaching more and more. Perhaps of great concern was that summer temperatures (without the influence of ENSO events) eventually exceeded the threshold levels. In two cases, Phuket and Jamaica, winter temperatures eventually exceeded the bleaching threshold on an annual basis.

87. One of the caveats that needs to be attached to the study of Hoegh-Guldberg (1999) is that it was done prior to the release of the IPCC Third Assessment Report. It used the now relatively optimistic IS92a scenario (a doubling of carbon dioxide by 2100). IS92a now tracks between B1 and B2 which are the lower edge of the IPPC scenarios. IS92a scenarios yield degree heating months values that are triple those that caused the major mortality events of Palau, Okinawa, Seychelles and Scott Reef. Given that future scenarios will quite possibly sit in the middle to high IPCC range, projections based on IS92a (Hoegh-Guldberg 1999) may be conservative relative to the recent IPCC scenarios.

Biological consequences of future climate change

88. If corals cannot change their tolerance to thermal stress over and above what they have exhibited in the last two decades, then the rise in sea temperatures is almost certainly likely to increase the mortality rates of corals at any one location. The approach of Hoegh-Guldberg (2001) was applied to estimating the number of catastrophic events that would occur as sea temperatures increase. As seen in the analysis done in the Pacific (Hoegh-Guldberg et al. 2000, Hoegh-Guldberg 2001), thermal stress (measured by degree heating months) increases steadily until thermal stress on reefs is 5-10 times greater than the thermal stress was in the worst affected areas of 1998. Operating objectively on the past behaviour of coral reefs, two categories of response were studied:

    (a) Reefs that bleach but recover: Reefs that experience 0.5 Degree Heating Months (DHM) during the summer months will experience mass bleaching. They will recover if stress levels return to previous levels.

(b) Reefs that experience almost total coral mortality: Reefs that are exposed to 3.2 DHM per year or more will experience almost complete mortality of their coral populations. This is conservative as reefs probably experience major mortality events at lower Degree Heating Month values (e.g. Scott Reef, 2.6 DHM in 1998).

89. To understand how reefs will respond to increasing thermal stress, we need two further assumptions. The first is that reefs that bleach every second year will experience a decrease in reef quality. This is logical given that bleaching has strong sub-lethal effects on both growth and reproduction (see section entitled "Sub-lethal impacts of thermal stress"). Equally, total mortality events that occur three times per decade will no longer have coral dominated reefs. This is clearly supported by the observation that reefs like those of Palau, NW Australia and Okinawa have not recovered fully from the 1997-98 mass bleaching event. Wilkinson (2002) sums this issue up in the Executive summary in relationship to the reefs showing the fastest signs of recovery since the last global mass bleaching event "There has been considerable recovery in the unstressed reefs of Southeast and East Asia and Palau, and also along the Great Barrier Reef of Australia, but it will take several decades before reefs return to pre-1998 status. There is broad concern that another Climate Change/El Niño event could arrest the recovery." The overwhelming conclusion however is that mass mortality events like those of Palau, Scott Reef and Okinawa cannot occur every 3-4 years without eventually bringing coral cover to close to zero. This assumption is probably highly conservative given that the anomaly size continues to grow (>> 3.2 DHM) in addition to the frequency.

90. These issues are recognised by Done et al. (2003, Table 1) in a useful table that defines the types of ecological impacts on coral reefs with an estimate of recovery times. "High level" and "catastrophic" ecological impacts have return times of 20 and 50 years, respectively. Clearly, even 3 "high level" events per decade would clear reefs of coral cover (let alone 3 "catastrophic" impacts which is probably closer to that posed by a 3.2 DHM event). Recent community modelling work has reinforced this conclusion. Using a cellular automaton model developed for coral communities, Johnson et al. (2003) have demonstrated that merely having events with DHM values of 1.2 every 10 years into the next century is enough to reduce coral cover by 50%. Adding stress levels like those seen when events (similar to that of 3.2 DHM) occur every 3-4 years produces outcomes in which coral cover is extremely remnant (Johnson et al. (2003).

91. The results of this analysis are striking. If reef-building corals and their symbionts do not change their tolerance (see below), then rapidly increasing sea temperatures will cause annual bleaching events by 2020 in Jamaica and Phuket, and by 2050 in Tahiti. More importantly, mass mortality events (years with DHM values of 3.2 or more) will increase steadily toward the middle and last half of the century. Using the criteria established above, reefs will shift to non-coral dominated states by 2020 in Jamaica, 2030 in Phuket and 2050 in Tahiti.

Escape clauses: Can adaptation match the rate of increase in sea temperature?

92. Faced with rising sea temperatures and the prospect of coral tolerances being exceeded, "adaptation" to these rising stress levels has been suggested as one view of the future (Done 1999, Done et al 2003). Simplistically, adding the same rate to

the thermal threshold of stressed corals as the seawater temperature is increasing over time would eliminate any increase in coral bleaching and mortality (Hoegh-Guldberg 2001). There is little evidence, however, of a strong adaptive (genetic) response by reef-building corals to the increase in thermal stress. It is important to realise that adaptation here is taken in the strict academic context of genetic change in the tolerance of populations or corals and not in the broader sense of Done (1999) which includes community compositional changes.

93. These have already been discussed above. The former lies at the core of increasing the threshold of coral populations while the latter represents changes that are likely to be negative as species are lost and reef resilience is decreased (see further discussion below). The problem is, as outlined earlier, rates of change are much higher than most of the environmental transitions seen in the recent geological record. The current growth of greenhouse gas concentrations is two orders of magnitude greater than seen during glacial transitions. Future growth of gas concentrations is even higher. There is also very little if any evidence that suggests that corals and their zooxanthellae have been adapting to the changes in sea temperature over the past 20 years. As mortality appears to be increasing not decreasing (see Hoegh-Guldberg 1999 and Wellington et al. 2001 for recent reviews), and thermal thresholds of coral populations appear to be in similar places as where they were 20 years ago (e.g. Hoegh-Guldberg et al 1997; Brown 1997), evidence at first glance appears to favour the suggestion that rates of change are exceeding the rates at which reef-building coral populations can adapt. To some, this may not be surprising given the slow growing, largely asexual organisms (corals) and their complex intracellular symbiosis (with a unicellular dinoflagellate protist).

94. Consideration needs to be given to processes that introduce change. Increasingly more tolerant genotypes are unlikely to arise due to mutation given the rarity of these events over the short periods involved. This leaves three possibilities. The first is that the population contains individuals that are more tolerant and that these are selected as stress increases. The second is that tolerant stock recruit from areas (e.g. lower latitudes) that are historically warmer. The last is by swapping their algal symbionts for other more tolerant varieties (Buddemeier and Fautin 1993).

95. Hoegh-Guldberg and Hoegh-Guldberg (2004) considered inherent variability as a source of tolerant genotypes, immigration of warm adapted genotypes, and Remaking the holobiont (The Adaptive Bleaching Hypothesis), and concluded that there was not a strong case for adaptation playing a role in modifying the thermal tolerances of the reef-building corals that make up today's coral reefs.

Where will the world's reefs be in 2050?

96. If there is not a strong case for adaptation playing a role in modifying the thermal tolerances of the reef-building corals that make up today's coral reefs, then reef-building corals will no longer dominate today's "coral" reefs by the middle of this century. In this intervening period, reefs will have progressively lower amounts of reef-building corals. There are several serious ramifications of coral reefs that are no longer dominated by reef-building corals. The first is that much of the productivity and nutrient dynamics of reefs and coastal waters is likely to change as corals become rare. Secondly, due to the combined effects of thermal stress and

increased carbon dioxide, the calcification on coral reefs is likely to be much reduced. This may led to the net erosion of reefs among other issues. The third is that biodiversity of coral reefs will be substantially reduced. And the last is that coral reef associated fisheries are likely to change as waters warm and benthic habitats change.

Productivity, nutrient dynamics and benthic habitats

97. Coral reefs are regions of high productivity within otherwise low productivity waters of the tropics (Darwin 1842; Odum and Odum 1955). While some reefs prosper in turbid, high nutrient waters inshore, most coral reefs are located in low nutrient waters. As stated at the outset, the highly evolved associations that typify coral reef are central to their success. Reefbuilding corals are the basis for the high levels of primary productivity of coral reef ecosystems. Photosynthetic energy captured by the zooxanthellae of corals is released directly to the water column as mucus or is consumed directly by filter-feeders, particle feeders and corallivores (Muscatine and Porter 1977, Hatcher 1988). Other primary producers are dependent on the habitats (e.g. substrate, back reef lagoons) that corals build. Coral reefs also have highly evolved nutrient dynamics, with most coral reefs acting as sinks for inorganic nutrients (Hatcher 1988). The net effect of these nutrient dynamics is that coral reefs often support primary production values that may be as much as several hundred fold higher than those of surrounding tropical oceans (Hatcher 1988).

98. While it is hard to generalise, reefs that lose reef-building coral cover undergo fundamental changes in the types of organisms that dominate the substratum. Red coralline algae, macrophytes and cyanobacteria tend to dominate reef substrates following the loss of reefbuilding corals. While little has been done so to understand how these new ecosystems function, primary productivity is almost certain to have varied from the original coral dominated ecosystem. Surfaces also play a key role in the nutrient dynamics of coral reefs and hence changes are likely within the nutrient dynamics of coral reefs. All of these changes are likely to have implications for organisms living on coral reefs.

99. A potentially important link between these types of changes and other organisms that are likely to be important to humans is that between coral bleaching and the incidence of the fish toxin, ciguatera. In French Polynesia, the benthic dinoflagellate, *Gambierdiscus* spp., is the primary causative agent when people eat poisoned fish. *Gambierdiscus* produces a toxin that builds up in the tissues of fish grazing reefs where it lives. Chinain et al. (1999) studied the seasonal abundance and toxicity of *Gambierdiscus* spp. on reefs around Tahiti and found peak densities of the dinoflagellate following a severe bleaching event in 1994. The authors speculated that coral morbidity may be another critical factor in the coral bleaching led to blooms of *Gambierdiscus* spp. by providing “new surfaces” for colonization by opportunistic species of macroalgae that are ideal hosts for *Gambierdiscus* spp. cells. The recent review of ciguatera by Lehane and Lewis (2000) also conclude that the link between global climate change, mass coral bleaching and incidences of ciguatera is strong and may explain the growing numbers of cases of poisoning in the Pacific and elsewhere. Again, the authors speculate that healthy coral populations are not good habitats for the cyanobacteria that manufacture the ciguatera toxin and hence events like coral bleaching and mortality that reduce the

abundance of corals will lead to an increase in the abundance of the toxin forming cyanobacteria.

Calcification

100. Calcification is one of the most important processes occurring on coral reefs. Through the energy expensive process of calcification, calcium carbonate has built up on coral reefs over time. The net effect is the large areas of carbonate reef that dot the world's oceans and the large deposits of calcium carbonate (limestone) dating from previous periods of reef growth. Through this process, the physical structure of the habitats in which thousands of species live has been created, and at a larger scale, coastlines protected by the oceanic barriers represented by coral reefs.

101. Reef-building corals and other symbiotic organisms produce the large amounts of calcium carbonate rock that are required to counter the significant forces of erosion. A fairly well supported hypothesis is that the dinoflagellate symbionts of these organisms produce the large amounts of energy needed to precipitate calcium carbonate (Barnes and Chalker 1990). The addition of CO2 above seawater will lead to the formation of carbonic acid and a decrease in the calcium carbonate saturation state. Gattuso et al. (1998) and Kleypas et al. (1999) calculated that doubling of atmospheric concentrations of carbon dioxide will lead to a 30% decrease in calcium carbonate saturation state. As calcification is directly dependent on the available pools of ions for calcification, these authors proposed that there would be a direct decrease in calcification. Since this work, several studies have shown unambiguously that calcification is essentially linearly dependent on . (Langdon et al., 2000; Leclercq et al., 2002). As coral reefs represent a fine balance between calcification and erosion, decreases of this magnitude are potentially problematic and could result in the net erosion of existing coral reef matrices. Normal rates of calcium carbonate deposition by corals range up to 20 cm $year^{-1}$ (extension rate of colony tips). Rate of reef growth (which is essentially the balance between deposition and erosion) is about 1-2 cm year-1 (Pittock 1999). This implies that 90% of the calcium carbonate deposited is removed by erosion. Within this simple perspective, a decrease of 30% in deposition should place reef systems into net erosion (by 20%).

102. Given the key roles that reefs play in providing habitat and protecting coastlines, the implications of the net erosion of coral reef structures are enormous. At this point in time, the process and potential rates of erosion (through physical and biological agents) is little understood. Clearly illuminating on these processes and their relationship to the rates at which calcium carbonate is likely to be deposited in the future should be a priority for research.

Biodiversity

103. Our understanding of the impact of losing coral as thermal stress increases is still in its infancy. Even the mildest climate change scenarios project substantial decreases in the amount of coral cover. Community changes like those seen by Loya et al. (2001) in Okinawa are broad sweeping, with the loss of sensitive coral species and the retention of more tolerant genera and species. While the reef may become more "tolerant", the loss of the high diversity of coral species may affect

other more global aspects such as reef resilience and recovery rates (Hughes et al 2003). How the changes in coral cover and diversity will affect the thousands of other organisms on coral reefs is still being examined. Organisms that depend on corals for food or shelter and which reproduce via external fertilization might be predicted to face extinction as their primary habitat corals become extinct. The response of fish communities over the short term has yielded some surprises. In the Seychelles, for example, Spalding and Jarvis (2002) found that the overall structure of fish communities had changed very little despite massive decreases (3-20 fold) in living coral cover after the 1997-98 bleaching event. Counter to this is the observation of rapid decreases in the abundance of species that are obligate corallivores.

104. These species are directly dependent on the presence of coral for their existence, disappearing quickly if coral is removed. The Orange-spotted filefish (*Oxymonacanthus longirostris*), a coral obligate, rapidly disappeared from Okinawan reefs after the 1998 bleaching event (Kokita and Nakazona 2001). Abundances of some fish also appear to increase following the loss of reef-building corals from reef communities. Lindahl et al. (2001), for example, showed an overall increase in fish abundance after the 1998 mass bleaching event on Tanzanian reef systems. This was largely linked to an increase in herbivores. Similar conclusions have been seen in studies at other sites by Chabanet (2002).

105. Other organisms are also likely to respond to changes in coral cover. For example, over 55 species of decapod crustacean are associated with living colonies of a single coral species, *Pocillopora damicornis* (Abele and Patton 1976, Black and Prince 1983). Nine of these are known to be obligate symbionts of living pocilloporid coral colonies. Branching corals of the genus *Acropora*, for example, have 20 species of obligates symbionts that depend solely on *Acropora* providing a habitat. It is important to point that the spacing of corals on a habitat may be critical for the reproductive success of coral associates that require sexual reproduction to proceed to the next generation. As corals become rare (i.e. spaced further and further apart), these organisms may be threatened as the chance of finding a partner or attaining successful fertilization becomes vanishing small.

106. Our understanding of the impacts of climate change on biodiversity is in its infancy and must be a high priority of future studies. While the pathway and time course of this change is undefined, few experts are suggesting that biodiversity will be unaffected by a rapid loss of reef-building corals from the system. The irony is that corals, by way of being asexual for at least part of their life cycle may be the least prone to extinction, being able to hang on at low density until conditions improve. On the other hand, the hundreds of thousands of dependent species, being highly dependent on sexual reproduction, may not.

Impacts on coral associated fisheries

107. In addition to the direct changes that are being seen in benthic fishes on coral reefs, there is growing evidence that fisheries are likely to change as warming continues. Fishing yields are likely to be reduced as reef viability decreases (Carte 1996; Munro 1996), leading to much reduced yields of protein for dependent human populations. Tropical fishery yields are already on the decline world-wide

in response to many other anthropogenic factors, and present problems may be exacerbated by the projected increase in tropical sea temperature.

108. There may also be other more subtle changes. There is now strong evidence that oceanographic and climatic variability may play a dominant role on fish stocks (Klyashtorin 1998, Babcock-Hollowed et al. 2001, Attrill and Power 2002). The evidence takes two forms. The first is that fish stocks are tightly correlated with measures of climate variability such as the El Niño Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) indices. The second is that climate shifts (e.g. 1°C increase in sea temperature in the late 1970s) produce major changes in dominant fish stocks in areas like the North Atlantic.

109. Klyashtorin (1998) has explored how major Atlantic and Pacific commercial species have varied in relationship to the atmospheric circulation index (ACI) from 1900-1994. ACI is a measure of basic atmospheric conditions in the Atlantic-Eurasian region. Atlantic and Pacific herring, Atlantic cod, European, South African, Peruvian, Japanese and Californian sardine, South African and Peruvian Anchovy, Pacific salmon, Alaska Pollock, Chilean jack mackerel undergo decadal changes in fish abundance that are tightly correlated (correlation coefficients of 0.7-0.9) with the ACI and other indices of climate variability. Similar conclusions were identified by Babcock Hollowed et al. (2001). These authors examined data sets for the North Pacific and Bering Sea and found strong associations between ENSO and PDO variability and data for catches of over 55 different fish stocks. The authors related these changes in fish stocks to changes in recruitment success driven by warmer or colder seas, which in turn affected aspects of the food webs that ultimately supported the species being fished.

110. There is probably no single explanation of why climate variability drives fish stocks. In some cases, subtle changes to conditions at crucial stages in the life history of the fish species may be important (e.g. conditions in estuaries, Attrill and Power 2002). Other effects may be broader in nature and have their effect through their influence on primary and secondary production in marine ecosystems. Large increases in catches of the western stock of the horse mackerel (*Trachurus trachurus* L.) in 1987 were associated with an increase in phytoplankton and zooplankton stock over the same period (Reid et al. 2001). The latter originated from the warmer conditions that in North Sea in 1987. The links between primary production are complex. Continuous Plankton Recorders (CPR), for example, have been deployed for more than 67 years in various oceans and tell an interesting story. The abundance of *Calanus* (a copepod and key planktonic species) is highly correlated with climate indices like the NAO with abundance in many declining since 1955.

111. These examples highlight the probability that fisheries are likely to experience major changes in the species that are available to be fished. While some species are likely to decrease, others may increase over time, suggesting that long term investments in specific fishing infrastructure may not be wise as the pace of environmental change increases. These issues will be discussed further in relation to the specific industries of the Great Barrier Reef.

Conclusions

112. There is now abundant evidence that the earth's ecosystems have already change substantially after only 0.6°C change in global temperature. Terrestrial ecosystems have seen dramatic changes in the distribution of alpine trees, grasslands, insects, birds and butterflies. Species from historically warmer climates are shifting in a poleward direction while species from colder climates are retracting. Similar changes have been seen in marine ecosystems. In some cases, structurally important organisms like reef-building corals appear to have experienced major impacts on their health and distribution. Coral bleaching, when corals loose their critical dinoflagellate plant symbionts, has increased from a local to global scale since the 1970s. Prior to 1979, cases of mass bleaching across regions are unknown in the scientific literature. The 1998 mass-beaching event, in which corals in all regions of the globe with coral reefs bleached, was the largest single event in recorded history. It coincided with the warmest sea temperatures on record in many reef systems. On some reefs, bleaching during 1998 eliminated reef-building corals as dominant organisms from reef structures where they have been dominant organisms for eons. These changes have led in turn to secondary changes in the distribution and abundances of organisms that use corals as primary habitat or as a food source.

113. Projections of changes in water temperature do not bode well for coral and the reefs that they help build. Already increases in water temperature of only 0.6°C since 1880 have increased the bleaching and mortality of reef-building corals across the planet. Projected increases of between 2 and 6°C by 2100 will increase stress levels on coral reefs from between 5 and 10 fold what they are on reefs today. These levels of change in sea temperature are unsustainable by corals growing where they are today, even under the milder scenarios in which seas only warm by 2°C. While genetic adaptation is discussed by a few authors (e.g. Done 1999), direct evidence of adaptation by corals is currently missing. Paleological arguments that reefs have been through similar changes are marred by the fact that current rates of change are probably 2-3 orders of magnitude higher than those seen under even the most rapid periods of climate change and the fact that Paleological methods lack the precision to see the important, human relevant changes of the order of 100-200 years. The latter is important in assessing the impact of past change at the human time scale (see discussion by Pandolfi 1996, 1999). While the fossil record might reflect the persistence of coral reefs over geological time, evidence of a decline in reef quality over 100 years is difficult or impossible to detect with current Paleological methods. Unfortunately, these are the time scales that are most important to humans.

Climate Change and the Great Barrier Reef

114. The Great Barrier Reef stretches along the coast of North East Australia and is the world's largest continuous reef system. It includes about 3,000 individual reefs, most of which are included in the largest and perhaps best managed marine park in the world. An Act of Parliament proclaimed the Park in 1975. In 1981, the Great Barrier Reef was inscribed on the World Heritage Register, a status increasingly being seen as an international obligation to maintain an area of world importance in a condition which will enable future generations to appreciate its unique features (GBRMPA 1998a). It has continued to play a leading role as one

of the most pristine examples of coral reefs globally. Unfortunately, as with coral reefs elsewhere, the Great Barrier Reef is facing challenges from both local and climate driven sources.

Regional changes in climate

115. Australia's average temperature on land has increased by approximately 0.6°C from 1910 to 1999. As with the global trends in temperature, most of this increase has occurred since 1950 (Collins and Della-Marta 1999; Lough 2000). 1998 was Australia's warmest year on record with the 1990s being the warmest decade closely followed by the 1980s (second warmest, Collins and Della-Marta 1999). Current rates of change are approximately 0.1 - 0.2°C per decade over most of Australia. As with the global ocean, sea temperatures in Australia's oceans are also increasing rapidly with rates approaching 1°C per century (Lough 1999; Hoegh-Guldberg 1999). Significantly, Lough (1999) who examined a wide array of data sources including *in situ* data loggers, blended satellite data and data from so-called "ships of opportunity", concluded that sea temperatures seen during the 1990s within the Great Barrier Reef were the highest on record.

116. Other changes in climate may have importance to corals and coral reefs. River flow can have major impacts on local inshore reef systems. Rainfall in Queensland is expected to decrease (–10% to +5% by 2030 and –35% to +10% by 2070; CSIRO 2001), which might be seen as benefiting the conditions under which corals grow due to lower run-off rates. Australia, however, is also projected to become considerably drier leading to greater rates of soil erosion which may see greater sediment loads. Again, human activity within the catchments that flow in the Great Barrier Reef can determine the magnitude of the change being effected by these changes in climate. Changes in climate (e.g. longer periods of drought) can also impact the amount of sediment and hence the health of coastal coral populations.

Bleaching on the Great Barrier Reef

117. The Great Barrier Reef has experienced seven mass bleaching events since 1979. These events were recorded in February-March of 1980, 1982, 1987, 1992, 1994, 1998 and 2002 (Oliver 1985, Hoegh-Guldberg and Smith 1989, Hoegh-Guldberg et al 1997, Oliver and Berkelmans 1999, Dennis 2002). There are no reports of mass bleaching events prior to 1979. Since 1979, bleaching events have become more intense and widespread, culminating in the statements that 1998 and now 2002 were the strongest bleaching events on record (Berkelmans and Oliver 1999, CRC 2002; Berkelmans et al. 2004).

118. Bleaching within the Great Barrier Reef Marine Park have always been associated with doldrums conditions in which the clear skies and calm seas led to a rapid warming of the upper layers of the water column (William Skirving, NOAA/AIMS, personal communication). These conditions conform to the doldrums conditions reported for a large number of other advents of mass bleaching. Elevated temperature accurately predicts the development of mass bleaching in the Great Barrier Reef. The worst cases of mass coral bleaching on the Great Barrier Reef in 1998 and 2002 were foreshadowed by elevated sea temperatures (Dennis 2003, Berkelmans et al. 2003; Berkelmans et al. 2004).

119. Elevated temperatures generally precede mass coral bleaching in the Park by as much as 2-3 weeks. The development of the sea temperature anomalies is compared between 1998 and 2002. In 1998, seas began to warm by late January with the development of the full anomaly occurring by early February. A similar pattern was followed by warming in 2002 except that it started earlier and was centred over the Coral Sea as opposed to being centred off south east Australia. The latter is reflected in the fact that the greatest exposures to stress (as indicated by the highest DHM values) occurred off the central portion of the Great Barrier Reef.

120. Berkelmans et al. (2004) examined the spatial correlation between sea surface temperature and bleaching during the 1998 and 2002 coral bleaching events on the Great Barrier Reef as shown in the following figure.

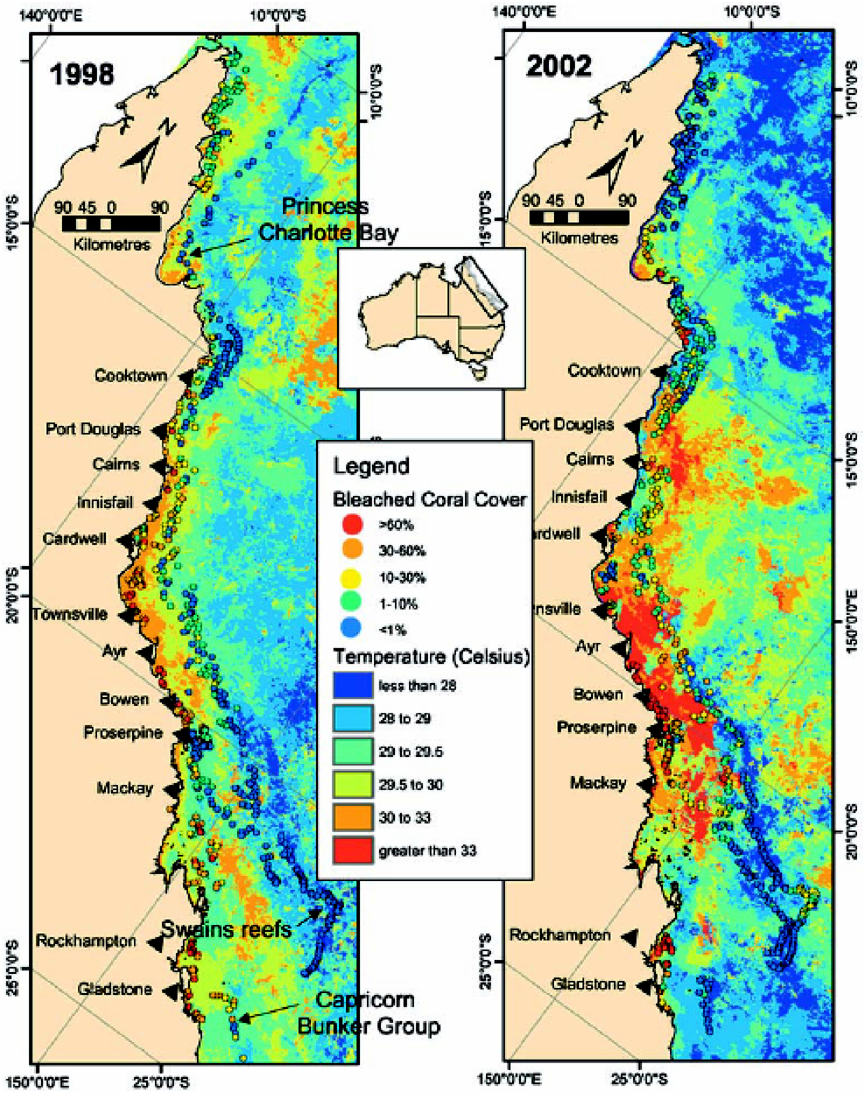

Figure 3: Berkelmans et al. (2004) raw aerial survey results of coral bleaching in 1998 and 2002 overlaid on the maximum 3-day sea surface temperature for every pixel during the warmest austral summer months (December– March)

121. Berkelmans et al. (2004) found approximately 42% of reefs bleached to some extent in 1998 with ~18% strongly bleached, while in 2002, ~54% of reefs bleached to some extent with ~18% strongly bleached. Their results from modeling of the relationship between bleaching and maximum 3 day sea surface temperature indicated that a 1 °C increase would increase the bleaching occurrence of reefs from 50% (approximate occurrence in 1998 and 2002) to 82%, while a 2 °C increase would increase the occurrence to 97% and a 3 °C increase to 100%. They concluded that these results suggest that coral reefs are profoundly sensitive to even modest increases in temperature and, in the absence of acclimatization/adaptation, are likely to suffer large declines under mid-range Intergovernmental Panel on Climate Change (IPCC) predictions by 2050.

The future: Climate change and the Reef

122. Given the scale of impacts being seen on coral reefs since the mid 1990s, there is substantial scientific evidence that priceless assets like the Great Barrier Reef are under severe threat from climate change as well as other factors such as over-exploitation of key fishery stocks and coastal land use.

123. How can we tell what the future holds for the Great Barrier Reef? One way, used by Hoegh-Guldberg (1999), is to use information about the past behaviour of coral reefs in the context of future conditions as projected by General Circulation Models (GCM). This approach is not without its shocking outcomes. If one assumes that reef-building corals are like other invertebrates and do not have extraordinary rates of genetic adaptation, then the current thermal tolerances for reef-building corals for corals on the Great Barrier Reef are exceeded annually by the middle of this century. Under these assumptions, corals will bleach more and presumably die more under increasing warming seas. There may be a short period in which populations may see the selection of tougher coral types. However, this period is likely to be short as sea temperatures continue to increase rapidly and the threshold of even these tough species are exceeded. It is important to note that the latter has already occurred when DHM values have risen to 2.5 or more and resulted with the loss of both thermally more tolerant as well as susceptible coral species.

124. The modeling conducted in Hoegh-Guldberg and Hoegh-Guldberg (2004) indicates that if the projected increases in sea temperature follow the trajectory suggested by the ECHAM4/OPYC3 trajectory for an IS92a scenario, reefs should soon start to decline in terms of coral cover and appearance. With a doubling of CO_2, thermal stress levels will soon reach the levels seen at isolated yet catastrophically affected sites in 1998. When these conditions arrive on reefs on the Great Barrier Reef more than three times per decade, coral cover should have declined to near zero. These dates are on average around 2030-2040 for southern, central and northern sectors of the Great Barrier Reef.

125. Putting adaptation and climate sensitivity aside, it is hard to argue against the notion that conditions, which have always resulted in massive mortality events, would not decimate coral populations if they arrived every 3-4 years. Coral cover at sites that experienced DHM values of 3 or more decreased by more than 50%. In some cases, coral cover was reduced to less than 5% of its previous values. Recovery of coral cover, even under the most optimal circumstances (low

latitude, low human impact) takes at least 10 years. Consequently, the assumption that reefs can sustain up to three of these events per decade is probably highly optimistic.

126. The conclusions drawn from the modeling in Hoegh-Guldberg and Hoegh-Guldberg (2004) were:

(a) Firstly, it is hard to argue from any available evidence that a loss of coral on reefs within the Great Barrier Reef is not highly likely. The thermal stress that corals will see over the next 30-50 years will regularly achieve and exceed the degree heating month values of events like 1998 and 2002. Major mortalities every year such as those that occurred in the Indian Ocean for example are not sustainable in Australian waters.

(b) Given the analysis of Done et al. (2003) and the implication that reefs will not be able to sustain catastrophic events more than 3 times a decade, reef-building corals are likely to disappear as dominant organisms on coral reefs between 2020 and 2050.

(c) While there is some variability in the impact of climate change according to latitude and proximity to the Queensland coast, the differences in the different trajectories are small. While Done et al. (2003) show that the tougher corals of inshore reefs like Magnetic Island may show delays in response to warming, these differences are at most a couple of decades.

Beyond 2100?

127. So far, the discussion of the impacts of climate change on the world's reefs has concentrated on the period from now to 2050 or 2100. Perspectives that take in longer time horizons stand to illustrate some of the benefits of scenarios that may not be distinguishable in the nearer future. For example, the families of IPCC scenarios discussed in this report are very similar in terms of temperature profile to around 2030 yet become very distinct in the second half of this century.

128. According to the long-term forecasts of global temperature, global greenhouse gas concentrations should stabilize around the end of this century at levels of CO_2 that will range between 450 and 1000 ppm. Going on the geological past, global temperatures will follow closely behind. While conditions for reefs will be hostile during the change, what will happen to reefs once temperatures, carbonate alkalinities and sea levels stabilize?

129. Hoegh-Guldberg and Hoegh-Guldberg (2004) modeled two possible futures. Under milder climate change scenarios the initial impacts, though great, leave some elements of the coral population in place such that when conditions stabilize, coral populations return. It is important to appreciate that the stabilization temperatures (+2-3°C) are found in some low latitude and inshore habitats (Berkelmans 2002). Therefore, there should be some individuals that migrate over long periods of time from low to higher latitudes. The process of reef growth might be assumed to have a lag phase of 30-40 years in it due to reduced flow of recruits between areas due to low coral stocks and other factors (e.g. those preventing a movement away from the phase shift). It is argued that

reefs return with only 70% of the original biodiversity due to the fact that several decades of inclement conditions is likely to be enough to eliminate many coral dependent species. Critical to this scenario are management practices that reduce human impacts on coral reefs to a minimum.

130. With more severe climate change, impacts are dramatic with the loss of some coral species and at least 50% of the organisms that live on coral reefs. The major impact is that organisms with a +5°C temperature tolerance are rare and hence coral stocks with higher thermal tolerance exist only in a few tiny patches (e.g. inshore Saudi Arabian waters). It consequently takes a very long time for coral reefs to even begin to recover coral cover. Temperatures also take much longer to stabilize due to the higher heat load and hence reefs may take several centuries to start to recover.

131. While these scenarios are highly speculative, they highlight several important issues. The first is that the mildest climate change scenarios are the only ones in which coral reefs have any chance of recovering in the near future. Secondly, they highlight the importance of reducing other pressures on coral reefs so as to maximise reef resilience which will be critically important as reefs are allow to recover if stabilization is achieved.

132. In all of the above scenarios, the “wild card” of how corals will adjust to the vastly reduced calcium carbonate alkalinities of future seas is not resolved. As with other factors like temperature, it is assumed that populations of corals will shift their gene frequencies as sea temperatures stabilize to include individuals that can calcify at these much lower calcium carbonate pools. It is important to point out, however, that this is optimistic given the fact that that calcifying organisms like reef-building corals do not thrive where salinity (a proxy for the concentration of ions like calcium and carbonate) is low. Similarly, carbonate production has been lower in the past when greenhouse gas concentrations have been higher (e.g. mid-Cretaceous, Wilson and Norris 2001, Wilson et al. 1998). Other factors, such as the growing link between disease and rising thermal stress have equally been left out. These factors would construe to promote the outcomes from rising thermal stress alone.

CONCLUSIONS

133. There is little doubt now that the future of the Great Barrier Reef is being jeopardized by the activities of humans (Hughes et al. 2002; 2003, Pockley 2003). Among these threats are coastal land use, over-fishing and climate change. As with the world’s coral reefs, climate change has grown from insignificance 20 years ago to the major threat facing the Great Barrier Reef (Hoegh-Guldberg 1999; Hughes et al 2003). So far (after 0.6°C of global warming), the Reef has probably escaped major lasting impacts from climate change. However, events like 1998 and 2002 remind us that it is the sea temperature of the future that should have us extremely worried. Projected increases in sea temperature in the Great Barrier Reef region are at best 1.5°C by 2100 and are at worst 5°C higher than current sea temperatures. In terms of comparing current conditions with those that will exist on the Great Barrier Reef in the future, sea temperatures that are typical of the northern tip of the Great Barrier Reef will exist at its southern end by 2040-50.

134. These temperatures will exceed the local thermal tolerances of reef-building corals on annual basis by 2030-60. The calculated thermal stress levels rise to several-fold higher than those seen in 2002 and lead to the highly probable conclusion that reefs dominated by coral will be rare in the Great Barrier Reef region by 2050.

135. It is important to point out that the rate of change is likely to depend on how we treat reef systems within the Great Barrier Reef Marine Park. The expansion of no-take or green zones will build reef resilience, a factor critical to how reefs will respond to the increasing frequency and intensity of thermal stress events. While some sectors of the fishing industry may see increasing numbers of no-take areas as negative relative to their key activities, there is now a large body of information that shows that protecting fish stocks through no-take zones will lead to increased fish populations in areas adjacent to these areas (e.g. Alcala and Russ 1998a,b).

136. Differentiating between the four scenarios explored in Hoegh-Guldberg and Hoegh-Guldberg (2004) is difficult up to 2040 due to model uncertainties. By 2050, however, the trajectories become distinctly different. Under the potential stabilization of carbon dioxide levels at 450-600 ppm, reefs are likely to recover over 50-100 years as the geographic reassortment of genotypes occurs. It is argued that the genetic stock required to migrate geographically is still available for most of the new thermal habitats. Calcium carbonate alkalinities are also expected not to have decreased to a point where significant calcification is still possible. One hundred years after stabilization, reefs, while much less biodiverse, may have dominant reef-building coral communities. Under scenarios that stabilize at carbon dioxide higher than 600 ppm, reefs may take much longer to return given that the genetic stock for corals that can grow at sea temperatures greater than 33°C are rare on the planet today. It will consequently take longer (if indeed it will happen at all) for warm adapted corals to find new sites within the shifting patterns associated with thermal habitats. The much more devastating effects of these sea temperatures may eliminate so much of the biodiversity associated with reefs that they may take thousands of years to return.

DECLARATION

137. I have made all the inquiries which I believe are desirable and appropriate and no matters of significance which I regard as relevant have, to my knowledge, been withheld from the Tribunal.

REFERENCES

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APPENDIX 1

Letter of instructions

ENVIRONMENTAL DEFENDERS OFFICE (QLD) INC.

Level 9, 193 North Quay
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Brisbane QLD 4000

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E-mail: edoqld@edo.org.au
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ABN 14 911 812 589

13 January 2007

Professor Ove Hoegh-Guldberg
Director
Centre for Marine Studies
The University of Queensland
St Lucia Qld 4067

By e-mail: Ove.Hoegh.Guldberg@gmail.com

Dear Professor Hoegh-Guldberg

Queensland Conservation Council Inc ats Xstrata Coal Queensland Pty Ltd & Ors

Objection to Mining Lease Application for Newlands Coal Mine Expansion

We act for the Queensland Conservation Council Inc ("QCC") in relation to an application lodged by Xstrata Coal Queensland Pty Ltd for a coal mine expansion at Newlands Coal Mine. QCC will argue, in the Land & Resources Tribunal, that the coal mine expansion should not be approved without imposing conditions to avoid, reduce or offset the greenhouse gas emissions from the mining, transport and use of the coal.

Background

Xstrata Coal Queensland Pty Ltd ("Xstrata") and its joint venturers[1] have applied for a mining lease under the *Mineral Resources Act* 1989 (Qld) ("MRA") and an environmental authority (mining lease) under the *Environmental Protection Act* 1994 (Qld) ("EP Act") for an open cut coal mine (ML 4761). The applications are for an additional surface area for extension of the Newlands Coal Mine, Wollombi No 2 Surface Area, at Suttor Creek approximately 129 km west of Mackay, known as the Newlands Wollombi No. 2 Project ("the Newlands Coal Mine Expansion").

The mine will produce up to 2.5 million tonnes per annum ("Mtpa") of run of mine ("ROM") black coal for a nominal annual average of 1.9 Mtpa product coal over a 15 year mine life, or 28.5 Mt of coal in total.

The coal from the mine will be transported to domestic and/or export markets for electricity production (thermal or steaming coal) and/or steel production (metallurgical or coking coal).

[1] Itochu Coal Resources Australia Pty Ltd, ICRA NCA Pty Ltd, and Sumisho Coal Australia Pty Ltd.

The total greenhouse gas emissions from the mining, transport and use of the coal from the mine are estimated to be 84.0 million tonnes of carbon dioxide equivalent ("MtCO2-e"). Of this total amount, 1.37 MtCO2-e (1.63%) comes directly from the mining operation itself. The bulk (98%) comes from the use of the coal overseas.

Expert evidence

The key evidentiary issues QCC will address in expert evidence are:

1. What is global warming and climate change, how serious a problem is it, and how does the mining, transport and use of coal contribute to these processes?

2. The likely greenhouse gas emissions from the mining, transport and use of the 28.5Mt of coal from the mine.

3. The contribution that the likely greenhouse gas emissions from the mining, transport and use of the coal from the mine will make to climate change and potential impacts of this.

4. The reasonable and practicable means to avoid, reduce or offset the likely greenhouse gas emissions from the mining, transport and use of the coal from the mine, including the costs of these measures being imposed.

5. The likely impacts of climate change on the Queensland economy.

We would very much value your assistance as an expert for QCC to address issue **1**, in particular the likely ecological impacts of global warming and climate change on the Great Barrier Reef (GBR), Australia, by 2050 and beyond.

Documents

We refer you to the following documents:

1. The Land and Resources Tribunal Guidelines for expert witnesses (Practice Direction No 11 of 2000) – available at http://www.lrt.qld.gov.au/LRT/proceedings/pd11.htm .

2. The objection dated 7 November 2006 lodged by QCC – available at http://www.envlaw.com.au/newlands1.pdf.

3. Directions made by the Land and Resources Tribunal on 27 November 2006 – available at http://www.envlaw.com.au/newlands2.pdf.

4. *Factual and Legal context of the QCC objection in the Queensland Land & Resources Tribunal to the Newlands Coal Mine Expansion* prepared by Chris McGrath, barrister – supplied by email.

Timeframe

There is a very tight timetable for the proceedings as follows:

1. Experts' affidavits are to be filed by **15 January 2007**;
2. Experts within similar field of expertise are to confer by **18 January 2007** with a view to resolving or narrowing any matters upon which they disagree;

3. Experts within similar field of expertise are to file and joint report by **22 January 2007** setting out the matters upon which they agree and any matters upon which they disagree, and the reasons for any disagreement;
4. The matter is set down for hearing in the Land and Resources Tribunal over three days commencing **31 January 2007**.

It may well be that the other parties will not rely on evidence from experts within your area of expertise and there will be no need for a joint meeting or joint report. At this stage, we do not know whether you will be required for cross-examination.

Your duty to the Tribunal

We emphasis that, in accordance with the Tribunal's guidelines for expert witnesses:

- You have overriding duty to assist the Tribunal on matters relevant to your area of expertise;

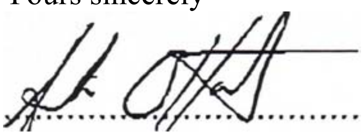
- You are not an advocate for QCC; and

- Your paramount duty is to the Tribunal and not to QCC.

We also emphasise that neither QCC nor its lawyers seek to influence your views in any way and we ask for your independent opinion to assist the Tribunal. Consequently, please note that any statements of fact or opinion in this letter of instructions, the above documents, or anything given or said to you by QCC or its lawyers relevant to the issues in your report do not constrain you in any way and are not intended to influence your views. We ask you to form your own opinion about the relevant facts and circumstances for the purposes of your report.

If you have any queries, please do not hesitate to contact me on (07) 3289 7991.

Yours sincerely



Anita O'Hart
Solicitor

Environmental Defenders Office (Qld) Inc

APPENDIX 2

Curriculum vitae of Professor Ove Hoegh-Guldberg

CURRICULUM VITAE

OVE HOEGH-GULDBERG

Centre for Marine Studies, University of Queensland

DATE AND PLACE OF BIRTH

26th September 1959, Sydney, New South Wales

EDUCATION

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

PRESENT POSITIONS

Professor of Marine Studies, University of Queensland (since 2000)
Director, Centre for Marine Studies, University of Queensland (since 2000)
Director, Heron Is, Low Isles and Morton Bay Research Stations
Deputy Director, ARC Centre for Excellence for Reef Studies
Visiting Professor, Stanford University

PREVIOUS ACADEMIC APPOINTMENTS

1999:	Associate Professor, School of Biological Sciences, University of Sydney
1995-98:	Senior lecturer, School of Biological Sciences, University of Sydney
1992-94:	Lecturer, School of Biological Sciences, University of Sydney
1989-1991:	Office of Naval Research Postdoctoral Fellow, Biological Sciences, U.S.C.
1991:	Lecturer, Department of Biology, UCLA

OTHER SIGNIFICANT APPOINTMENTS

2006-present	Member, Royal Society, London, Marine Advisory Network (MAN)
2006-present	Member, Board of reviewing editors, Science Magazine
2004-present	Member, Royal Society, London, Working Group on Ocean Acidification
2004-present	Member, Australian Climate Group
2001-present:	Chair, GEF-WB-IOC Working group on climate change and coral health
2001-present:	Member, World Bank-IOC Synthesis Panel TRG Coral research.
2001-present:	Member, Int. Scientific Advisory Committee, GBR Research Foundation
2002-present:	Member, Scientific Advisory Committee, QLD gov committee on Biodiversity
1998:	Visiting scientist, European Oceanographic Center, Monaco
1998:	Research faculty, Indiana Institute of Molecular Biology
1995-97;1999:	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

1999:	The 1999 Eureka Prize for Scientific Research
1996:	Sydney University Award for Excellence in Teaching
1989:	Robert D. Lasiewski Award (best Ph.D. in animal research, UCLA)
1988:	UCLA Distinguished Scholar Award
1988:	Organismic Animal Biology Award, UCLA
1987:	Australian Museum/Lizard Island Bicentenary Fellowship
1987:	Departmental Fellowship Award, UCLA

1984-88 Sydney University Travelling Scholarship (Ph.D. scholarship to U.S.)

PROFESSIONAL SOCIETIES

Science Magazine (Board of Reviewing Editors, 2006-present)
International Symbiosis Society (Governing councilor, 2004-present)
Australian Coral Reef Society (Council and president; 2000-2002)
International Society for Reef Studies (Council; 2002-present)

CURRENT ADMINISTRATIVE RESPONSIBILITIES

Centre Director

The Centre for Marine Studies co-ordinates research and teaching in marine studies at the University of Queensland. It now comprises of 60 staff members, and over 40 postgraduate and Honours students at its St Lucia hub. The Centre also runs Heron Island Research Station, the largest research station on the Great Barrier Reef; Moreton Bay Research Station, a modern facility on North Stradbroke Island in Moreton Bay; Low Isles Research Station, a small station on the inner, northern Great Barrier Reef; a suite of vessels of various capacities; and Pinjarra Aquatic Research Station, an aquaculture facility a few kilometres from the main University campus. Details of these facilities can be obtained from the Centre's web site: http://www.marine.uq.edu.au.

I was appointed as the inaugural Director in January 2000 and have spent the last 5 years building the Centre for Marine Studies with my academic and research team. Since moving to the Centre, I have overseen growth from an annual budget of under $2 million to one that is now over $6 million, from a staff and student body of 12 to over 90 people. During that time, I have also been responsible for attracting major funding for the infrastructure associated with the Centre (e.g. $6.5 million, systemic infrastructure, 2002) and have brought major research initiatives to the Centre (e.g. GEF-WB-IOC project; $28 million; 2004-2008, to be coordinated by UQ). In 2005, I was a significant partner in an ARC Centre of Excellence bid (>$20 million, 2005-2010), in which I approached JCU and ANU and proposed a joint bid. Research stations have also been completely refurbished under my Direction, with use of the three stations having increased by an average of 35% over the past four years. Currently over 5,000 scientists and students stay at the University stations. The Centre has also developed several world-class academic programs including the Great Barrier Reef Study Program (http://www.marine.uq.edu.au/GBRSP/overview.htm) and the Stanford Australia Program (http://osp.stanford.edu/program/australia/, see also below).

My role as Centre Director includes overseeing both academic (> 50 students and scientists) and general staff (>24 people), being responsible for operating budgets in excess of $6.5 million; directing three research stations and an aquaculture facility, academic and research programs and developing long-term strategies for the Centre. I report directly to the Executive Dean (Professor Michael E. McManus) and serve on University committees such as the Executive Dean's Advisory Committee.

Director, Stanford Australia Program (Stanford University)

I have an active interest in establishing new milestones for marine education. As part of this, I have developed the Stanford Australia Program (http://osp.stanford.edu/program/australia/) over the past 2 years. This program is now in its third year. I am currently the Program Director and visiting Professor at Stanford University, responsible for five full-time courses that run out of the Centre. I directly teach and coordinate two of these courses (Coral Reef Ecosystems and Targeted Research Project). In addition to coordinating this program, I give lectures, run field exercises and perform assessment on the 48 students that enter the program each year. I am also responsible for the development of new subject areas and continued program development in association with the Overseas Study Program at Stanford University. The Australia Program is now one of the most popular programs running through Stanford University.

Chair, GEF Bleaching Targeted Research Group

The Intergovernmental Oceanographic Commission (IOC) and World Bank Coastal Program established the Global Coral Reef Targeted Research and Capacity Building Project in 2000. As part of this, I chair one of six expert groups that focused on coral bleaching and related ecological factors – coordinating the input from 12 leading scientists, helping establish research plans and setup budgets. As part of my duties, I also represent this group on the Project Synthesis Panel. Details of the groups can be found at www.gefcoral.org and the bleaching expert group http://www.ioc.unesco.org/coralbleaching/index.html. This project has now passed into the active stage and has been awarded $11 million (USD) from the Global Environment Facility (GEF), with a further $8 million (USD) being raised from the World Bank, IOC and other partners. I have played a significant role in crafting the strategy behind this project, including writing the document "Four Oceans" and being lead author on the document that set out the management of the execution of the project. The latter led to the University of Queensland being selected to coordinate the first five year phase of the project. Total funding for this project is $28.09 million (USD) plus an estimated $50 million (USD) in leveraged resources over the first five year period. I am currently leading the group designed to setup the Project Execution Office.

Marine Animal And Plant Symbiosis Laboratory (www.cms.uq.edu.au/MAPSLab)

I have maintained an active research career in the area of marine symbioses and am responsible for one of the largest academic laboratories. As part of this, I lead a large research group that includes nine postdoctoral fellows, thirteen postgraduate and three Honours students (see next section). I currently am involved in $2.35 million in funding; $1.2 million has been awarded to me as senior investigator. I have been responsible for the supervision to completion of nine Ph.D, three M.Sc. and over 12 Honours students. My research activity within MAPSLab has generated over 90 reviewed publications plus two patents.

RESEARCH TEAM MEMBERS

My research interests span the following topics: Marine biology; evolution, physiology, biochemistry and molecular biology of plant-animal symbioses, coevolution, biology of hermatypic corals, calcification, coral bleaching, climate change, invertebrate larvae, physiology/biochemistry of larval development.

The following people are currently members of my research group.

Post-graduate students (current):

Ms Tracy Ainsworth (50%)
Ms Jo Davy (60%)
Ms Ida Fellagara (100%)
Mr David Harris (100%)
Ms Meegan Henderson (50%)
Ms Angela Lawton (100%)
Ms Paulina Kaniewska (80%)
Mr Guy Marion (100%)
Ms Ruth Reef (50%)
Mr Ayax Rolando Díaz Ruíz (60%)
Ms Eugenia Sampayo (10%)
Mr Simon Albert (20%)
Mr Juan Carlos Ortiz (70%)
Ms Charlotte Kvennfors (50%)
Mr Jez Roff (50%)
Ms Narinratana Kongjandtre (60%)
Mr Udo Engelhardt (100%)

Post-doctoral fellows (current):

Dr William Leggat
Dr Mauricio Rodriquez-Lannetty
Dr Guillermo Pullido-Diaz
Dr Saki Harii
Dr Tyrone Ridgway
Dr Selina Ward
Dr William Loh
Dr Kenneth Anthony
Dr David Kline
Dr Olga Pantos

Honours students (current):

Ms Rachel Middlebrook (100%)
Ms Jessica Jarrett (100%)

PUBLICATIONS

Refereed articles

1. **Hoegh-Guldberg**, O. (2006). Perspective: The complexities of marine protected areas. Science 311: 42-43.

2. 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 (in press)
3. Ainsworth TD, Kramasky–Winter E, Loya Y, **Hoegh-Guldberg** O and Fine M.(2007) Coral disease diagnostics: what's between a plague and a band? Applied And Environmental Microbiology (in press)
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13. Fine M, Roff G, Ainsworth T D, **Hoegh-Guldberg** O (2006) Phototrophic microendoliths bloom during coral "White Syndrome". Coral Reefs, (DOI 10.1007/s00338-006-0143-4).
14. Franklin, DJ, Molina, C. M., **Hoegh-Guldberg,** O (2006) Increased mortality and photoinhibition in the symbiotic dinoflagellates of the Indo-Pacific coral *Stylophora pistillata* (Esper) after summer bleaching. Marine Biology 149: 633–642
15. **Hoegh-Guldberg**, O. (2006), Low coral cover in a high-CO2 world, J. Geophys. Res., 110, C09S06, DOI:10.1029/2004JC002528.
16. Leggat, W., Ainsworth, T.D., Dove, S., and **Hoegh-Guldberg**, O. (2006) Aerial exposure influences coral bleaching patterns. Coral Reefs DOI: 10.1007/s00338-006-0128-3 Published online: 13 June 2006
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Media articles

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INVITED SYMPOSIA, ABSTRACTS AND PRESENTATIONS (SINCE 1998 ONLY)

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2. Lawton, A, **Hoegh-Guldberg**, O (2006) the effect of temperature on the photosynthetic and respiration rate of reef building corals. ACRS conference, Abstract.
3. Ainsworth, TD, **Hoegh-Guldberg**, O (2006) Pathology and Microbial Ecology in Coral Disease and Bleaching. ACRS conference, Abstract.
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8. **Hoegh-Guldberg**, O. (2005) Challenges for tourism in a warming world. Responding to coral bleaching and climate change. Australian Reef Tour operators workshop, Cairns, October 2005.
9. **Hoegh-Guldberg, O**. (2005) Coral-algal symbiosis in a changing environment. Invited Seminar, Interuniversity Underwater Institute, Eilat, Israel, June 3, 2005
10. **Hoegh-Guldberg**, O. (2005) Climate change and coral reefs - the burning issues. Invited seminar, Weizmann Centre, Israel, June 3, 2005
11. **Hoegh-Guldberg**, O. (2005) Coral reefs in a warming, acidifying ocean. Invited seminar to Intergovernmental Panel on Climate Change, Canberra, March 13, 2005
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13. **Hoegh-Guldberg, O. (**2004) The Great Barrier Reef in the Current Century of Rapid Environmental Change. University of Pennsylvania, October 18, 2004
14. **Hoegh-Guldberg**, O. (2004) Coral Bleaching: A Multinational, Multidisciplinary Program to Address a Critical Global Issue. Invited talk to CZAP, Sydney.
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16. **Hoegh-Guldberg**, O. (2004) The Great Barrier Reef and Climate Change. Invited seminar to the DAVOS leadership retreat. August 2004.
17. **Hoegh-Guldberg**, O. (2004) Low coral cover in a high CO2 world. In the special symposium entitled "The Ocean in a High CO_2 World." hosted by IOC-UNESCO and SCOR, Paris, May 2004
18. **Hoegh-Guldberg**, O. (2004) Changing environmental envelopes. Degraded coral reefs or coral reefs off Sydney? Invited seminar at the Great Barrier Reef Water Quality conference, Townsville, March 2004.
19. **Hoegh-Guldberg**, O. (2004) Great Barrier Reef: Coral, climate and the future. Invited speaker at launch of major report. World Fund for Nature, Sydney March 2004
20. Vestergaard, O, **Hoegh-Guldberg**, O, Unluata, U (2003) Understanding Coral Bleaching Across Four Oceans - Addressing CBD's Specific Workplan On Coral Bleaching Convention of Biological Diversity (CBD), SBSTTA 8, 10-14 March 2003, Montreal,
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22. **Hoegh Guldberg,** O. (2003) Invited Plenary and Congress Welcome: Bleaching of coral symbionts: A global threat 4-International Symbiosis Society Congress Programme, August 17, 2003; Halifax, Canada
23. **Hoegh Guldberg,** O. (2003) The Physiological Ecology of Mass Coral Bleaching. Invited talk at US Coral Reef Task Force Meeting: Coral Reefs, Climate, & Coral Bleaching June 18 – 20, 2003; Turtle Bay Resort Hotel, Oahu, Hawaii
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27. **Hoegh-Guldberg**, O (2003) Coral Bleaching TRG: Introduction and synthesis. 4th Coral Bleaching Working Group meeting (synthesis and planning), IOC/UNESCO, Paris, 29-31 March 2003
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33. Johnson CR, Dunstan PK, **Hoegh-Guldberg** O (2002) Predicting the long term effects of coral bleaching and climate change on the structure of coral communities. In: Proc Int Soc Reef Studies Eur Meeting, Cambridge, Sept, Abstr vol 50
34. **Hoegh-Guldberg**, O. (2002) Critical mechanisms in coral bleaching. GEF-WB-IOC Puerto Morelos field workshop, Mexico 9-22 Sept 2002
35. Franklin D.J., **Hoegh-Guldberg**, O., Jones, RJ, and Berges, JA (2002) Oxidative stress and depressed variable fluorescence correlate with dinoflagellate death in the coral *Stylophora pistillata* GEF-WB-IOC Heron Island field workshop, Great Barrier Reef, 25 Feb-18 March 2002:
36. Johnson, CR, Dunstan, PK, **Hoegh-Guldberg**, O (2002) **Predicting the long term effects of coral bleaching and climate change on the structure of coral communities.** GEF-WB-IOC Heron Island field workshop, Great Barrier Reef, 25 Feb-18 March 2002:
37. Smith, C.R., Dove, S., **Hoegh-Guldberg**, O, Wilson, K. and van Oppen, M. (2002) The heat stress response of Acropora millepora: a population perspective. GEF-WB-IOC Heron Island field workshop, Great Barrier Reef, 25 Feb-18 March 2002
38. **Hoegh-Guldberg**, O. (2001). "Sizing the impact: Coral reef ecosystems as early casualties of climate change" invited plenary at conference "Detecting the Fingerprints of Climate Change". Gland, Switzerland.
39. **Hoegh Guldberg,** O. (2001) The Future Of Coral Reefs: Integrating Climate Model Projections And The Recent Behaviour Of Corals And Their Dinoflagellates. Invited seminar, Situating the Environment, Conference, St Lucia.
40. **Hoegh Guldberg,** O. (2001) Tropical Marine Science. Setting priorities for universities. Invited talk, Queensland State Development.
41. **Hoegh Guldberg,** O. (2001) Climate change and implications for fisheries. Invited Plenary, Fisheries Summit May 1 2001
42. **Hoegh Guldberg,** O. (2001) Climate Change and Australia's coral reefs. ACRS 2001 Annual Conference of the Australian Coral Reef Society, Magnetic Island, Townsville, Queensland, 6-8 July 2001.
43. **Hoegh Guldberg,** O. (2001) The Great Barrier Reef: Our Dead Sea? Invited Plenary at the Photosynthesis Conference, Sydney, June 2001.
44. **Hoegh Guldberg**, O. (2000) Photoinhibition and climate change: why reefs bleach. Invited seminar at Max Planck Institute, Bremen, Germany, June 16, 2000
45. **Hoegh Guldberg,** O. (2000) How will coral reef ecosystems react to projected changes in sea temperature? Invited Plenary speaker, Copenhagen ASLO meeting and Special session: SS27 - Climate change, weather patterns and aquatic systems

46. **Hoegh-Guldberg,** O. (2000) The future of coral reefs: integrating climate model projections and the recent behaviour of corals and their dinoflagellates. Proceeding of the Ninth International coral reef symposium, October 23-27, 2000. Bali, Indonesia,
47. Ward, S, Harrison, PJ and **Hoegh-Guldberg**, O (2000) Coral bleaching reduces reproduction of scleractinian corals and increases susceptibility to future stress. Proceedings of the Ninth International symposium for Reef Studies. October 23-27, 2000. Bali, Indonesia,
48. Ridgway, T., **Hoegh-Guldberg**, O. (2000). Reef recovery in disturbed coral reef ecosystems. Ninth International Coral Reef Society Symposium. October 23-27, 2000. Bali, Indonesia,
49. Carter, D.A., Gava, N., Loi, T.H., Loh, W.KW and **Hoegh-Guldberg**, O. (2000) Genetic diversity of symbiotic dinoflagellates ("zooxanthellae") inhabiting different scleractinian coral species. Australian Society for Microbiology Conference, Cairns, 8-11 July 2000
50. **Hoegh Guldberg,** O. (2000) Corals - Sentinels of Global Change. Australian Marine Science Association, plenary, Townsville, Friday, 31 March 2000
51. **Hoegh-Guldberg**, O. (1999) Coral bleaching: from molecular mechanism to ecological impact. University of Technology, Sydney.
52. **Hoegh-Guldberg**, O. (1999) Coral bleaching and Climate Change in the Pacific. **Key Note Address**, Pacific Science Congress (to be given, July 4-9, 1999).
53. **Hoegh-Guldberg**, O. (1998) Coral bleaching: physical factors, genetic variability and symbiotic dysfunction. Key Note Address, Special session on Coral Bleaching.
54. **Hoegh-Guldberg**, O. (1998) Coral Bleaching: biochemical and physiological explanations of reef-scale phenomena. University of California, Los Angeles (April1998)
55. **Hoegh-Guldberg**, O. (1998) Coral reefs and change: molecular explanations of reef-scale phenomena. Distinguished Speaker Program, California State University, Northridge
56. **Hoegh-Guldberg**, O. (1998) The secret life of the coral polyp. Departmental seminar, Biology Department, California State University, Northridge (March 1998)
57. **Hoegh-Guldberg**, O. (1998) Coral reefs and change: molecular explanations or reef scale phenomena. Ecology, University of Georgia (Feb 22, 1998)
58. **Hoegh-Guldberg**, O. (1998) Photoinhibition, photoprotection and the earliest steps in coral bleaching. Biology and Biochemistry, University of Houston (Jan 1998)
59. **Hoegh-Guldberg**, O. (1998) Myths and legends of the larval life. Ecology and Evolution, University of Houston (Jan 1998).

INTERNET AND MULTIMEDIA TEACHING PROJECTS

I have an active interest in teaching using new technologies and in using the media to bring about public education on science related issues. I have also been featured in over 100 news, radio and TV documents and programs. Some of the more significant ones are:

1. **Hoegh-Guldberg**, O. (1997) Reef Education site: Executive Producer, http://www.reef.edu.au; Finalist, Australian Internet Awards, Best science site (Contact: Leanne Hunter).
2. **Hoegh-Guldberg**, O. (1996) Internet Art Auction: 1996 (Aug 15-30, 1996)
3. **Hoegh-Guldberg**, O. (1996) "Raising the dead: interactive solutions to teaching comparative zoology" http://www.reef.edu.au/Teach/
4. Interactive CD-ROM (1994): "One Tree Island: Research in action".
5. Interactive CD-ROM (1996): Antarctica: a virtual experience (demonstration)
6. Documentary (Quantum: Question of Survival series) (1994).
7. Educational video: "One Tree Island: The key to saving the Great Barrier Reef " Producer: Soren Jensen and Ove Hoegh-Guldberg
8. NSW Scratchies: "Reef Treasures" series (1996): Organised the NSW lottery commission to run a series of Scratchy cards based on the conservation of coral reefs.
9. Documentary "Silent Sentinels", Quantum special feature. Producer Richard Smith. Science consultant. Also contributed footage. Award-winning.
10. Documentary "Aquarius: Undersea Lab", Quantum special feature. Producer David Clark. Contributed underwater footage to production. Premier release, Dec 14 2002.
11. IMAX film "Antarctica" 1992 – was ice diver, subject and camera assistant (McMurdo Base). Award-winning.