

**Coral Reefs and Environmental Change: Adaptation to What?** A. BARRIE PITTOCK.  
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## **Coral Reefs and Environmental Change: Adaptation to What?**

### **Abstract:**

The present concern about future climate change and sea-level rise due to the enhanced greenhouse effect is put in the context of past changes. Best estimates of future changes are detailed, with an explanation of methods and uncertainties. Considerable progress is being made in regard to estimates of future sealevel rise and its regional variation, and towards predicting likely changes in the behaviour of the El Nino-Southern Oscillation (ENSO) and tropical cyclones. Changes in rainfall amounts and intensity, and in extremes of surface temperature are other critical climatic variables for coral reefs. Impacts on coral reefs will result from a combination of stresses arising from several aspects of global change, including stresses due to sea-level rise, extreme temperatures, human damage (from mining, dredging, fishing and tourism), and changes in salinity and pollutant concentrations (nutrients, pesticides, herbicides and particulates), and in ocean currents, ENSO, and storm damage. These may be exacerbated by any reduction in calcification rates of corals due to changes in ocean chemistry. In view of ongoing uncertainties regarding future rates of change, especially at the local scale, impact and adaptation assessments cannot provide unequivocal answers, but rather must be couched in terms of probabilities and risk. Reef communities which are presently under stress are likely to be particularly vulnerable. Both autonomous and managed (or planned) adaptations should be considered.

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## **INTRODUCTION**

Living coral reefs in general (although not each individual reef) have survived over many millions of years, despite large amplitude fluctuations in climate and sea level over the glacial-interglacial cycles (Kinzie and Buddemeier, 1996). What is new in the present is the probability of rapid rates of warming and sea-level rise combined with greatly increased

atmospheric carbon dioxide ([CO.sub.2]) concentrations, other stresses due to human interference, and of course the special values humans place on particular reefs and ecosystems as protective barriers, tourist attractions, breeding grounds for fisheries, and so on.

Warming at the end of the last glaciation was on average about 1 [degrees] C per thousand years (although there were certainly much more rapid warmings over short periods in some localities such as the North Atlantic). Over the last century warming has been about 0.5 [degrees] C. Projected warming over the next 100 years is in the range of 0.9 to 4.5 [degrees] C (IPCC, 1996, Chapter 6). For thousands of years during the last deglaciation sea level rose, at an average rate of about 1 m per century, but for short periods, when there were large meltwater pulses, at 2 to 4 m per century (Fairbanks, 1989). Best estimates from tide gauge records suggest a rise of 10 to 25 cm over the last 100 years, while projections suggest a rise in the next 100 years of about 15 to 95 cm (IPCC, 1996, Chapter 7).

Thus expected rates of temperature and sea-level rise next century are not in themselves unprecedented, but they will occur in a very different context, coming on top of a warm, high-stand interglacial period, and accompanied by much higher atmospheric [CO.sub.2] concentrations which will affect ocean chemistry (Buddemeier, 1994; Buddemeier and Fautin, 1996; Gattuso et al., 1999b).

Impacts on coral reefs are bound to be very complex, with multiple stresses acting in concert, extreme events playing a major role, and questions as to whether absolute levels of key variables, or rates of change, are more critical. From a climatological viewpoint, it is relatively easy to create a list of relevant variables (e.g., air or sea temperatures, rainfall and salinity, photosynthetically active [PAR] and ultraviolet radiation [UVR] levels, sea level, storm surge heights, tropical cyclone intensity and frequency, turbidity of water, nutrient levels, etc.). It is, however, well nigh impossible, at least at present, to quantify many of these variables in terms of either future absolute levels or rates of change. Moreover, many of these changes will vary with location and produce highly location-specific impacts. This means that we should not be expecting one-off "predictions" of global change impacts at some future

date in any quantitative sense, although we may be able to go some way down the path to doing sensitivity analyses, or better still, risk analyses.

The potential impacts of environmental change need to be assessed through sensitivity and risk analyses, in order to:

- \* identify critical thresholds and risks, as part of a global assessment, to help develop greenhouse gas emission reduction policy under the terms of the United Nations Framework Convention on Climate Change (FCCC),

- \* identify, and quantify risks and threats which may require a management or policy response at the local or regional level.

One purpose, therefore, is a global one of helping to decide what is a level of greenhouse gas concentrations which would lead to "dangerous interference in the climate system" (FCCC Article 2). While this is a global purpose, it can only be answered by looking collectively at a lot of local assessments, and then making the highly subjective value judgement as to whether the sum of the local impacts constitutes a "dangerous" impact in some global sense. Our goal in such an exercise must therefore be to try to identify thresholds of absolute amounts (e.g., a maximum temperature for coral), or rates of change (e.g., a maximum rate of sea-level rise), which give rise to unacceptable or "dangerous" local situations. This involves not only some assessment of the value of the reef communities per se, but of their wider function, e.g., as breeding grounds for fish, as protective shields for coasts and islands, or as sources of materials for atoll building. Impacts must, therefore, be assessed not only for reefs in isolation, but in their context as a resource or part of a wider ecosystem in a physical as well as biological sense.

The second purpose, that of guiding local or regional management or policy, boils down to a similar type of local assessment, although perhaps less concerned with thresholds, and more with continuous adjustment or adaptation.

In both cases, there are two types of adaptation to consider, "autonomous adaptation," which is what the reefs would do by themselves, and "planned adaptation," which involves conscious human interference to in some way assist in the persistence of some "desirable" traits of the

system. The first may involve more rapid growth of coral, changes in species composition, or evolution of particular species in response to changed temperatures or other variables. Planned adaptation might involve "seeding" of particular reefs with different species better adapted to higher temperatures, or attempts to limit increased sediment, pollutant, or freshwater inflow into a closed lagoon, or the widening of channels to allow greater tidal flow. Such natural or engineered adaptations of course raise questions as to what is "adaptation" and what is fundamental change. What we might hope to do eventually in impact assessments is to explore these possibilities and limits so as to see what management and policy might acceptably do, and what level of change is unacceptable. Before we can do that, however, we need a better understanding of what the environmental changes might be, and, if we cannot get firm predictions, then what might be the possibilities and risks. This is the real purpose of this paper, which focusses on the risk from climatic, sea-level and ocean chemistry changes which might occur over the next century.

## CLIMATIC AND OTHER FACTORS AFFECTING CORAL REEFS

### Carbon dioxide changes and ocean chemistry

It has been recognised for over 100 years that the burning of fossil fuels, and deforestation, has been leading to increasing concentrations of carbon dioxide ([CO.sub.2]) in the atmosphere. More recently, measurements of [CO.sub.2] concentrations of air sealed in bubbles in ice cores from Greenland and Antarctica have shown that during the previous two glaciations atmospheric concentrations were around 200 parts per million by volume (ppmv), compared to about 270 ppmv in pre-industrial times since the last glaciation, and some 360 ppmv in 1995.

The Intergovernmental Panel on Climate Change (IPCC, 1992, 1996) identified a broad range of possible future greenhouse gas and sulfur emissions (the latter lead to small sulfate particles in the lower atmosphere) in the absence of emission policies. Figure 1 shows the consequent range of scenarios for actual [CO.sub.2] concentrations, from the highest (IS92e), through a midrange (IS92a) to the lowest (IS92c). For other greenhouse gases and sulfur, the IPCC scenarios contain a similar range of emissions, assuming a strong link between [CO.sub.2] and sulfur

emissions because the burning of fossil fuels is the major cause of both. Thus most scenarios include increasing emissions, and concentrations, of both [CO.sub.2] and sulfur. However, because of the increasing use of sulfur emission reduction technology, the future strength of this link is uncertain and sulfate concentrations may level out or decline. Greenhouse gases lead to a global surface warming, while sulfate particles lead to some regional cooling, so a decline in sulfate concentrations would increase the global warming.

[Figure 1 ILLUSTRATION OMITTED]

The importance of the increase in actual [CO.sub.2] concentration in the atmosphere to coral reefs is that it leads to a reduction in the Ca[CO.sub.3] saturation state of the upper ocean, which in turn slows down the rate of calcification of coral (Buddemeier, 1994; Buddemeier and Fautin, 1996; Gattuso et al., 1999a, b). For this reason it is important to clearly distinguish between the concentration of actual [CO.sub.2] and that of "equivalent [CO.sub.2]," which is often quoted. "Equivalent [CO.sub.2]" concentration is the [CO.sub.2] concentration which would have the same radiative forcing effect in the atmosphere as the sum of the radiative forcings from all the greenhouse gases apart from water vapor. As shown in Figure 1, actual [CO.sub.2] concentration is likely to be double pre-industrial values by about 2070. Equivalent [CO.sub.2] concentrations will double several decades earlier. As shown by Gattuso et al. (1999b), a doubling of actual [CO.sub.2] concentrations in the atmosphere could lead to decreases in calcification rates of 9-30%, which could have serious implications for the resilience of corals to other environmental stresses, including storm damage and sea-level rise.

The adoption of protocols to reduce greenhouse gas emissions, under the terms of the FCCC, might be expected to reduce [CO.sub.2] concentrations, future warmings and sea-level rise, relative to those resulting from uncontrolled emissions. Wigley (1998) has calculated the effect of the Kyoto Protocol with three assumptions for the post 2010 emissions from developed countries (Annex B countries in the Protocol), which are the only countries for which reductions are required under the terms of the Protocol. Relative to the baseline of the mid case IS92a emissions scenario, if the developed countries reduce their emissions by

5% by 2100, as required by the Protocol, and then maintain constant emissions to 2100, the reduction in projected [CO.sub.2] concentration by 2100 is from about 710 ppmv to about 665 ppmv. The corresponding reduction in projected warming is about 0.15 [degrees] C, or 7.5% of the total warming, and that in projected sea-level rise is about 2.5 cm or some 5% of the total. These results are for a "best estimate" of the global climate sensitivity (discussed below). The smallness of the effect is due to several factors:

1. Global emissions would have to be reduced by some 60-80% to achieve a stabilisation of greenhouse gas concentrations (depending on the stabilised concentration level), because greenhouse gases have long lifetimes in the atmosphere.
2. Emissions from developing countries are still allowed to grow, and they will dominate the total emissions by the middle of the 21st century.
3. There is a lag built into the climate system, largely due to the large heat capacity of the oceans, so the oceans will continue to warm (and expand) long after stabilisation of greenhouse gas concentrations.

### Global average warming

Global average warming is a response to the increased radiative forcing due to all greenhouse gases, including the [CO.sub.2] concentrations shown in Figure 1, and other greenhouse gases including methane, nitrous oxide and water vapor (this last being a variable dependent on surface temperature, thus providing a reinforcing or positive feedback effect). It will be reduced, mainly in the northern hemisphere, by the concentrations of the shorter-lived sulfate particles (which vary regionally), scenarios for which are at least as uncertain as (and different from) those for [CO.sub.2].

All global climate models (GCMs) show warming in response to increased greenhouse gas concentrations, but the sensitivity varies considerably between models. If the atmospheric [CO.sub.2] concentration is doubled and a new equilibrium climate is reached, IPCC has recognised a range of global mean warmings from the GCMs of between 1.5 and 4.5 [degrees] C. This so-called "climate sensitivity" is for

a highly idealised situation used to compare models. In reality, [CO.sub.2] and other greenhouse gases are increasing gradually, leading to a "transient" response of the climate system, with lags due to the large heat capacity of the oceans.

Figure 2 shows the upper and lower limit scenarios for global warming up to 2100, based on the IPCC 1995 scenarios. The solid curves show the range of warmings predicted on the basis of the IS92e (upper limit) and IS92c (lower limit) greenhouse emission scenarios, with assumed sulfur emissions varying in proportion to [CO.sub.2] emissions out to 2050 and then held constant. The dashed curves have the same greenhouse gas scenarios, but with sulfur emissions assumed constant at 1990 levels. With varying sulfur emissions, the lower limit at 2100 is about 0.9 [degrees] C warming, and the upper limit 3.5 [degrees] C. Constant sulfur emissions leads to a upper limit warming of 4.5 [degrees] C, but no change in the lower limit. The moderate IS92a greenhouse gas emission scenario, with the varying sulfur emissions and the "best guess" climate sensitivity, leads to a global average warming by 2100 of about 2.0 [degrees] C.

[Figure 2 ILLUSTRATION OMITTED]

### Hydrological cycle and rainfall intensity

In addition to global average warming, there will be an enhancement of the hydrological cycle, due to higher temperatures leading to more evaporation, and thus more rainfall on average to maintain the global moisture balance. The increase in rainfall will not, however, be uniform. While GCMs tend to show that precipitation will increase on average at high latitudes, results in the tropics are more mixed (Whetton et al., 1996a), although with fairly general increases in rainfall intensity, i.e., there will be proportionately more heavy falls (Fowler and Hennessy, 1995; Hennessy et al., 1997). The last point is illustrated in Figure 3, which shows simulated summer daily rainfall intensities over tropical Australia, under present (1 x [CO.sub.2]) conditions, and doubled [CO.sub.2] conditions (from Suppiah et al., 1998). While not occurring everywhere in the model simulations, this phenomenon is likely to occur over many coral reefs and nearby land areas, leading to at least temporary

reductions in salinity due to freshwater influxes, and to possible increases in turbidity and pollution due to increased erosional flood-flow events on land.

[Figure 3 ILLUSTRATION OMITTED]

#### Visible and ultraviolet radiation

Photosynthetically active radiation (PAR) is essential for coral reef growth (Kleypas, 1997) even though an excess (often associated with subaerial exposure and high temperatures) can lead to bleaching (Glynn, 1997), while ultraviolet radiation (UVR) may be deleterious (Shick et al., 1997). Levels of PAR and UVR exposure will be strongly affected by any change in cloud amount and optical depth, could be reduced by rising sea level unless coral growth keeps up with the sea level, and would be affected by any change in turbidity due to changes in wave action or changed sediment or nutrient loading from terrestrial runoff.

Ultraviolet radiation reaching the sea surface is also reduced by ozone in the atmosphere. In the tropics the ozone occurs mainly in the stratosphere above an altitude of about 20 km. Ultraviolet radiation at the surface increases by about 1 to 2% per 1% decrease in column ozone amount, depending on its wavelength and the sloping path through the atmosphere (Lubin and Jensen, 1995).

Stratospheric ozone is depleted by chemical reactions due to various substances of recent human origin, principally chlorofluorocarbons, which are now regulated under the terms of the Montreal Protocol. These substances are likely to peak in concentration, if the Protocol continues to be observed, in the next few years. Measurements indicate that in recent decades total column ozone amounts have decreased by 4 to 5% per decade in the midlatitudes, and by greater amounts in polar regions, particularly over the Antarctic in spring. However, in the tropics (20 [degrees] N to 20 [degrees] S) no significant trends have been observed from 1979 to 1992 (Herman et al., 1996), and none are expected (WMO, 1995). Thus widespread increases in UVR in regions where there are coral reefs are not to be expected.

Nevertheless, significant local changes could occur in both PAR and

UVR due to systematic changes in cloud cover brought about by climate change. While cloud cover is simulated in climate models, large uncertainties remain about future changes in cloud amount and optical properties. At present we are not in a position to predict such changes, but they could well accompany shifts in the position of the Inter-Tropical Convergence Zone (ITCZ), the South Pacific Convergence Zone (SPCZ) or changes in the El Nino-Southern Oscillation (ENSO).

### Regional performance of climate models

IPCC (1996) statements suggest that agreement on changes in precipitation at the regional (i.e., sub-continental) scale is poor. However, a comparison of regional simulations with five recent GCMs with surface mixed-layer-only oceans ("slab-ocean" models) and five GCMs with full deep ocean representation ("coupled-ocean" GCMs), reveals fairly good agreement, except for parts of the southern hemisphere (Whetton et al., 1996a). Regional comparisons and validations of these models were made for their simulation of the present climate over the southern continents and the South Pacific by Whetton et al. (1996b). The major differences in the southern hemisphere occur principally over Australia in summer between slab-ocean and coupled-ocean GCM results. These appear to be due to a simulated lag in warming of the Southern Ocean in the coupled-ocean models. Figure 4 shows the range of warmings, per degree warming at the Equator, for the five slab-ocean and five coupled-ocean models. The slab-ocean models show more warming in the Southern Ocean than at the Equator, but the coupled-ocean models show less.

[Figure 4 ILLUSTRATION OMITTED]

The lag in the Southern Ocean was further demonstrated in a long simulation with the CSIRO coupled-ocean GCM in which it was taken out to 3 x [CO.sub.2] and then the [CO.sub.2] concentrations were stabilised for a further several hundred years. During the transient increase in [CO.sub.2], the Equator to latitude 55 [degrees] S temperature difference increased, but after stabilisation of [CO.sub.2] concentrations, this temperature difference decreased to look more like the slab-ocean result. This is important because it appears to affect the climate changes even in low southern latitudes (e.g., in tropical Australia), and may affect

the strength of the South Pacific oceanic gyre, and possibly tropical cyclone and ENSO behaviour.

Whatever the accuracy of the large-scale picture from the global climate model simulations, it will be necessary to obtain more regional and local detail by "downscaling" to the spatial resolution relevant to local topography, coastlines, and smaller scale weather phenomena such as tropical cyclones, topographically forced rainfall, and sea breezes. This can be done by using regional climate models (RCMs), driven at their boundaries by global climate model output (a process called "nesting") (McGregor et al., 1993). It can also be done by statistical downscaling, which relies on statistical relationships between local weather or climate and the larger-scale climate features which the GCMs can simulate (Karl et al., 1990; Wilby and Wigley, 1997). There are, however, limitations on the use of statistical downscaling, as the method generally relies on long records of local climatic data to establish the statistical relationships. In many locations such records do not exist, and even where they do, they may not include variations as large as may occur under climatic change. Moreover, year-to-year variations in climate may be a poor analogue of climatic change, since the two are driven by different mechanisms.

The bottom line for studies of global change and coral reefs is that in most locations where there are coral reefs, nested modelling or other downscaling has not yet been done, so that even if the GCM simulations were reliable, local simulations are not available. Such downscaling has been undertaken for parts of the United States, Europe, Australia, and some parts of Asia, but not over the South Pacific, the Caribbean and some other locations of interest. This is largely because developing countries in these regions do not have the resources to do it, and international agencies, with their focus on "capacity-building," are in general reluctant to fund "scientific research," however necessary it may be to understand the potential impacts of global change and the adaptations which may be necessary to cope with these changes.

It should also be noted that GCMs will only provide a good basis for regional climate change scenarios in much of the Pacific when they can model the ITCZ and the SPCZ reliably. Many GCMs at present do a poor job with these major climatic features (Pittock et al., 1995).

## Regional temperature and rainfall changes

The pattern of sea surface temperature warming at 2070 relative to that at 1880, as simulated by the CSIRO coupled-ocean GCM (Hirst et al., 1996), is shown in Figure 5. This shows maximum warmings occurring at high latitudes in the North Atlantic and North Pacific. In the tropical Pacific warmings are greatest in the presently relatively cool eastern section, although warmings in the western tropical Pacific are still in excess of 2[degrees]C. Warmings are least in the Southern Ocean, and in the Arctic where sea-ice remains.

[Figure 5 ILLUSTRATION OMITTED]

Shifts in location of critical or representative isotherms of sea surface temperature can readily be constructed from GCM output. This was done for the difference between the control case (present climate), the 2 x [CO.sub.2] case, and the 3 x [CO.sub.2] case for the 24 and 27 [degrees] C annual mean isotherms, since the 24 [degrees] C isotherm corresponds roughly with the main areas of coral reef formation, and 27 [degrees] C is about the present lower limit for tropical cyclone genesis (although tropical cyclones can travel over considerably cooler water once they have formed). Neither of these temperature criteria will necessarily apply under changed climatic conditions, but their movements are indicative of the sensitivity of the climate/reef system. We also looked at the movement of the 18 [degrees] C isotherms for the coldest months of the year (taken as January in the northern hemisphere, and July in the southern), which are about the low temperature limits for coral reef formation (Kleypas, 1997; Kleypas and McManus, 1999). Results (not shown) indicate poleward movements by several hundred km of all three isotherms, between the present and 2 x [CO.sub.2], with about half that additional movement from 2 x [CO.sub.2] to 3 x [CO.sub.2]. The latter is because the radiative forcing change decays exponentially with increasing [CO.sub.2] concentration. There is also a very large relative movement polewards and eastwards of the 24 and 27 [degrees] C isotherms in the eastern tropical Pacific Ocean and in the Caribbean and tropical Atlantic. Polewards movement is significantly greater in the northern hemisphere than in the southern, due to the thermal lag in the Southern Ocean.

On the face of it, these results suggest that significant changes might be expected in conditions affecting coral reefs. However, all the caveats mentioned above regarding uncertainties and inconsistencies between different GCMs must be taken into account, and to understand effects on particular reefs will require downscaling. Indeed, if one is concerned about the effect of ambient temperatures on coral bleaching, it may be necessary to model changes in water temperatures inside the reef lagoons on spatial scales of tens of metres, and even the effects of deepening of the lagoons and increasing wave energy due to sea-level rise.

Regional and especially local rainfall changes are even more uncertain and complex than for temperature. Not only will critical larger-scale features like possible changes in the locations of the ITCZ and SPCZ, and their seasonality and year-to-year variations, need to be determined, but changes in smaller scale features such as tropical cyclones and orographic effects will also need to be assessed. Ideally, RCMs will be used, perhaps with double-nesting, to go to spatial scales of ten km or less, but it will be some time before this can be done for many locations, and it will of course be an expensive process. Rainfall changes will then need to be fed into simulations of changes in salinity, due either to direct freshwater addition to the sea surface, or via runoff from adjacent land. The latter may affect not only salinity, but also carry with it sediment loading, nutrients and other pollution such as agricultural chemicals (Larcombe et al., 1996), all of which may affect coral reefs. These influxes may be made more severe by increased rainfall intensities and associated greater soil erosion.

### Sea-level rise

Global average sea-level rise is due to a combination of several effects (IPCC, 1996, Chapter 7):

- \* tectonic effects associated with land-sea movements and the shape of the oceans;
- \* thermal expansion of the ocean water;
- \* changes in water volume from melting or growing mountain glaciers;

\* changes in the volumes of the grounded ice sheets of Greenland and Antarctica; and

\* minor contributions from water storage in dams and changes to groundwater volume due to human activities.

Local sea-level rise, which is what matters for any one reef, is a combination of global mean sea-level rise, local tectonic effects, and local mean variations of sea level from the global average (which are a function of currents, atmospheric pressure and other effects). For many impacts, what is even more important are local extremes of sea level due to time-varying effects such as ENSO, seasonally varying currents, inputs of less dense fresh water from rainfall and runoff, and storm surges due especially to tropical cyclones.

Tectonic effects are too slow to affect the global mean sea level on timescales of centuries, but they do affect some coasts which may be rising (e.g., the Scandinavian coast, due to the ongoing isostatic rebound from loss of the huge weight of the last glaciation ice sheet) or sinking (e.g., parts of the east coast of North America and of the United Kingdom) relative to the sea. These local effects must be allowed for in averaging tide gauge records.

Thermal expansion occurs due to warming of the ocean waters, and is a complex function of heat transport into the oceans, which varies greatly from place to place and is affected by salinity, sea ice cover and formation, and other effects. Sea ice formation results in the rejection of brine which is both near freezing and dense due to its high salinity. This causes sinking and the formation of cold dense bottom water which can flow long distances in the deep ocean. Reduction of bottom water formation will effectively warm the deep ocean.

Most of the world's mountain glaciers are in retreat this century, due to a combination of warming and highly localised changes in precipitation. Estimates can be made from observations of the location of the terminuses of many glaciers, supplemented by measurements of the thickness of some, and two- and three-dimensional modelling of a few. In general, observed rates of retreat are mainly explicable by warming of around 0.5 [degrees] C over the last century (e.g., Haeberli, 1994), and

estimated retreat can be crudely converted to water volume (Gregory and Oerlemans, 1998).

Depletion of groundwater reserves in some regions due to exploitation for irrigation has contributed extra water to the oceans, but this has been at least partly cancelled by rising water tables in irrigation areas and by water stored in dams. The net effect is thought to be small.

Best IPCC (1996) estimates for global mean sea-level rise are about 1 to 10 mm per year, leading to rises of 5 to 25 cm by 2030, 10 to 60 cm by 2070, and 15 to 95 cm by 2100 (see Fig. 6). About half of this is due to thermal expansion, with most of the rest due to melting of the mid- and low-latitude mountain glaciers. Antarctica was expected to have a small negative effect on sea-level rise, due to increased snow accumulation, but more recent results by O'Farrell et al. (1997) suggest that the net effect of Antarctica in the next century may be close to zero. Greenland, which is warmer, may make a small positive contribution to sea-level rise due to melting.

[Figure 6 ILLUSTRATION OMITTED]

Estimates of each of these terms in the global sea-level rise equation are rather uncertain, with the thermal expansion component being particularly susceptible to downwards revision as better modelling of the deep ocean circulation is done (England, 1995; McDougall et al., 1996). This is illustrated by recent estimates of the thermal expansion term by McDougall (CSIRO Division of Marine Research) and colleagues, assuming the IS92a greenhouse gas emissions scenario for global warming, using the CSIRO coupled ocean-atmosphere model with two different mixing schemes in the ocean (the older iso-pycnal or ISO scheme, and the newer Gent and McWilliams or GM scheme). The latter, which gives more realistic ocean features, reduces the thermal expansion term by about one third. But as this is only about half of the total sea-level rise, this correction only reduces the best estimate total sea-level rise for 2100 by about one sixth, from 50 to about 42 cm.

According to Hopley and Kinsey (1988), growth rates of coral reefs during the Holocene sea-level rise showed a modal value of 7-8 mm [yr.sup.-1] for framework construction, with higher rates up to 16 mm

[yr.sup.-1] for less dense branching corals. For the predicted rates of sea-level rise over the next century of around 1-10 mm [yr.sup.-1], this suggests that coral reefs in general will be able to keep up in the short term, although with some changes in species composition. However, Hopley and Kinsey suggest that over longer time scales reefs as a whole have a potential maximum vertical accretion rate of no more than 8 mm [yr.sup.-1], with a potential for progressive drowning of reefs if sea-level rise exceeds this rate over long periods. Moreover, the higher-[CO.sub.2]-induced decrease in calcification rates may be expected to progressively reduce this threshold.

Sea level will not rise uniformly around the globe. This is due to different rates of warming in different parts of the global ocean, variations in atmospheric pressure on the ocean surface, and the effects of ocean circulations and varying wind stress changes (see for example, Gregory, 1993; Cubasch et al., 1994). McDougall and colleagues have made new estimates of the regional variations in sea-level rise based on the CSIRO coupled-ocean GCM with the GM mixing scheme. Regional variations are typically up to [+ or -] 50% of the global average. More work is needed to verify the robustness of the spatial patterns, but they suggest that impact and adaptation assessments should not assume global uniformity.

In addition to mean sea-level rise, variations in time at particular locations are important. One major cause of interannual variability, especially in the tropical Pacific, is the ENSO cycle. During El Nino years sea level in the eastern tropical Pacific can be up to 50 cm above that in La Nina years, and vice versa in the western tropical Pacific (Wyrтки, 1985). Smaller amplitude variations associated with ENSO also occur at places far removed from the tropics. As ENSO behaviour may change with global warming, this may contribute to changes in the extended periods of local sea levels above or below normal, which can be important for aspects of coral reef biology including coral bleaching.

The other major contributor to variations in local sea level is the storm surge, especially due to tropical cyclones (Anthes, 1982; Hubbert et al., 1991; Konishi, 1995). Depending on bottom topography and storm characteristics, such surges can add up to several metres to local sea level

for periods of hours or days, and in addition these are associated with large and powerful waves which can damage reefs and transport debris across reef flats and lagoons. A temporary lowering of sea level is also possible with tropical storms, if they generate strong off-shore winds. Thus changes in the climatology of storm surges may have major effects.

## Tropical cyclones

Tropical cyclones, the generic term for non-frontal tropical low pressure systems, are variously called "typhoons" (NW Pacific), "hurricanes" (N. Atlantic and NE Pacific) and "severe tropical cyclones" (SW Pacific and SE Indian Ocean), when they reach wind speeds in excess of 33 m [sec.sup.-1]. Such storms derive their energy from evaporation from the ocean and associated condensation in convective clouds near their centre (Holland, 1993).

Gray (1968, 1975) found that the frequency of tropical cyclone formation ("genesis") is related not simply to sea surface temperature, but to six environmental factors:

- \* large values of low-level rotation ("relative vorticity") in the broad vicinity;
- \* the Coriolis parameter (which is related to the rotation of the Earth, and requires that the location be several degrees of latitude from the Equator);
- \* weak vertical shear of the horizontal winds (i.e., wind differences at different levels should not be large enough to disperse the storm);
- \* high sea surface temperatures (generally above about 26-27 [degrees] C) and a deep surface warm layer in the ocean;
- \* a deep layer of relatively unstable air; and
- \* lots of moisture in the lower and middle troposphere.

So the shift of the 27 [degrees] C isotherm discussed above, however suggestive it may be, is far from the whole story. Attempts to apply Gray's six variables to predict tropical cyclone genesis under different

climatic regimes are so far inconclusive (Watterson et al., 1995), and an improved version is needed to account for climatic change.

There is controversy about the ability of GCMs and even RCMs, at relatively coarse horizontal resolution, to reliably simulate tropical cyclone genesis, paths and intensities (Evans, 1992; Lighthill et al., 1994; Broccoli et al., 1995) due to the complexity of tropical cyclones. Generally it is conceded that intensities will only be approximated by simulations at resolutions of about 30 km or finer. However, at coarser resolutions climate models do seem to be able to realistically simulate average tropical cyclone genesis regions and tracks (not those of individual storms in a weather-forecasting sense) (Walsh and Watterson, 1997).

Genesis regions around Australia under 1 x and 2 x [CO.sub.2] conditions as simulated by the CSIRO RCM at a resolution of 125 km, nested in the CSIRO slab-ocean GCM show fairly realistic locations of cyclone genesis in the control case, and the locations do not change significantly under simulated 2x [CO.sub.2] conditions. However, the same simulations show cyclone tracks extending further polewards in the 2x [CO.sub.2] case (see Fig. 7) (after Walsh in Suppiah et al., 1998; Walsh and Katzfey, in preparation). This is at least partly related to higher sea surface temperatures, which sustain the cyclone intensities longer. An important caveat is that these simulations are nested in a slab-ocean GCM, and results may be different in a coupled-ocean GCM. This has yet to be tested, although, as sea surface warming occurs in coupled-ocean GCMs also, a similar result is expected.

[Figure 7 ILLUSTRATION OMITTED]

Henderson-Sellers et al. (1998) give some credence to results using a thermodynamic estimation of maximum potential intensity (MPI) of tropical cyclones due to Holland (1997), which indicate that under doubled [CO.sub.2] conditions MPI may increase by 10-20%. This result is supported by simulations of some 51 storms under 1 x and 2x [CO.sub.2] conditions using a high-resolution (18 km) hurricane prediction system, effectively nested in a GCM (Knutson et al., 1998), and by analyses done in CSIRO at 30 km resolution, shown in Figure 8

(from Walsh in Suppiah et al., 1998). The latter two experiments both suggest that it is not only the maximum potential intensity that increases, but also the average intensity. While Holland points out that this increase is against a background of large year-to-year variability, any general increase would result in a shift towards a greater frequency of extreme events, which would tend to dominate the damage impacts.

[Figure 8 ILLUSTRATION OMITTED]

Another complication arises in that tropical cyclone occurrence, especially in the Pacific, has been shown to be highly correlated with the state of the ENSO variations (Revell and Goulter, 1986; Evans and Allan, 1992). This means that reliable estimates of tropical cyclone behaviour under enhanced greenhouse conditions must await reliable simulations of the behaviour of ENSO, as discussed below.

The El Nino-Southern Oscillation (ENSO)

As discussed in part already, the state of the ENSO phenomenon under enhanced greenhouse conditions is important to reefs because it affects local sea level, the occurrence of tropical cyclones, cloud cover and rainfall. It is also related to ocean currents.

Recent behaviour of ENSO, with a long sequence of El Nino events in the 1990s, has led to controversy as to whether this is part of normal ENSO inter-decadal variability (e.g., Harrison and Larkin, 1997; Rajagopalan et al., 1997), or due in part to global warming (Trenberth and Hoar, 1996, 1997). Trenberth and Hoar argue that the evidence suggests that ENSO is moving more into a El Nino-dominated mode as global warming takes place, but others disagree as to the statistical evidence of any real change, given the relatively short record of ENSO variability on these timescales.

Modelling evidence is also confusing, mainly because coarse-resolution GCMs do not well simulate detailed ENSO behaviour, while most finer-resolution models of ENSO have limited domains and may be questioned regarding assumptions made as to deep ocean temperatures and currents at their boundaries, particularly under climate change conditions.

What seems critical to this question is how the temperature contrast

between the eastern and western tropical Pacific changes with global warming. This is what drives (with some feedbacks to the ocean) the so-called "Walker Circulation," an east-west circulation in the tropical Pacific atmosphere, which is the atmospheric component of ENSO. We have started to look at this in long transient simulations with two versions of our coupled-ocean GCM, one with the ISO mixing parameterisation, and the other with the GM mixing scheme. The ISO simulation suggests no change in the strength of the Walker Circulation, while the GM simulation has it substantially weakening. At present it is uncertain which is more correct, but this question may be resolved when the coupled-ocean GCM is run at finer spatial resolution globally.

### Ocean currents

Ocean currents are poorly simulated in GCMs due to inadequate horizontal resolution. This applies especially to coastal boundary currents and those flowing around islands. Very broadscale features, such as the strength of the ocean gyres, may be better captured, and conceivably these could change if there are changes in the strength of the trade winds and the midlatitude westerlies.

A simple measure of the potential change in the strength of the mid-latitude westerlies, which in the southern hemisphere drive the South Pacific Gyre, is the pressure difference between 45 and 55 [degrees] S. Results of long simulations with the CSIRO coupled-ocean GCM with the GM mixing scheme show only a minor difference between the transient and control runs, with changes in the pressure difference at about 3 x [CO.sub.2] of only 10%. This is not a dramatic change, and would probably be swamped by local changes, which will only be captured by much finer-scale models.

### Non-climatic changes

Growing population pressures in the vicinity of many coral reefs are already putting these reef communities under increasing stress. Over-fishing, especially by destructive methods; mining of coral rock and sand; engineering modification for ports and harbours; and increasing sediment and pollution loadings are common (Wilkinson, 1997).

Terrigenous sediment influx to the Great Barrier Reef lagoon has been well documented by Larcombe et al. (1996). They indicate that land-clearing and farming activities have increased this flux, which is largely controlled by infrequent high intensity rainfall events such as those due to tropical cyclones and monsoon rains. Dispersal of the plumes in the lagoon is controlled by prevailing wind and current patterns.

Reefs surrounding small populated islands are particularly vulnerable to sewage and chemical influxes. With the development of more modern agriculture, influxes increasingly include excess fertilisers and herbicides, both from continental coasts and islands.

The greatest impact of climate change, and especially of the effect of increasing CO<sub>2</sub> concentrations on ocean chemistry, will come from the synergistic combination of these changes with existing natural climatic and anthropogenic stresses. The latter, at least, can potentially be controlled (Wilkinson, 1997) if the will to do so exists.

## TOWARDS RISK ASSESSMENT

### Quantifying uncertainty

Attempts to quantify the impacts of climate change have been plagued by the large uncertainties at each step in the process. Many of these, as regards regional and local climate changes, have been discussed above. If one adds to these the uncertainties regarding the biophysical consequences of a given climate change on complex ecosystems, and of the response mechanisms and adaptations possible, one is easily led to the concept of an "explosion of uncertainty" (Henderson-Sellers, 1993). This large range of uncertainty makes scientific advice often appear unhelpful to decisionmakers.

One point to remember here is that much of the uncertainty regarding climate change is due to the uncertainty of future human activities, as represented in the range of greenhouse gas emission scenarios and consequent global warming and sea-level rise scenarios (Figs. 1, 2 above). Here one can look separately at the consequences of each emission scenario, to gain an idea of the differing effects of human behaviour which we, as decisionmakers, may be able to alter.

Beyond that, the wide range of uncertainty obtained by considering the products of several ranges of uncertainty, without considering the likelihood of each combination, can be very misleading. In fact, multiplying distributions for two or more sources of uncertainty together produces a more peaked probability distribution, since the products of extremes can be largely eliminated as highly improbable (Jones, 1999). This is illustrated in Figure 9, which shows estimates of the probability of temperature changes of various magnitudes by 2030 along the northern coast of Australia. While the full range, based on the IPCC range of global warmings (Fig. 2 above) and the range of regional warmings per degree global warming, is 0.36 to 1.04 [degrees] C (CSIRO, 1996), the 10th and 90th percentiles are 0.47 and 0.86, respectively, with a most probable (median) value of 0.66 [degrees] C. This is a 43% reduction in range for only a 20% chance of missing extreme values.

[Figure 9 ILLUSTRATION OMITTED]

This approach does not eliminate uncertainty, but it does usefully distinguish between more or less probable outcomes, and thus provides a basis for risk assessment.

### Identifying thresholds

To assess risk, climate impacts must be explored to determine appropriate thresholds. An impact threshold is any degree of change that can link the onset of a given critical ecological or socio-economic impact to a particular climatic state or states. Biophysical or environmental thresholds represent a distinct change in the conditions or level of performance or function of an ecosystem. For coral reefs, such thresholds, possibly involving combinations of several environmental variables, might apply, e.g., to coral bleaching, to whether a reef can keep up with sea-level rise, or to loss of species diversity.

Some of these thresholds will be absolute values of one or more variables which must not be exceeded if we are to avoid undesirable consequences, while others will involve rates of change. The two kinds of thresholds are illustrated in Figure 10. Threshold A is a rate of change threshold, superimposed on the upper and lower bound estimates for scenarios of global warming. This could represent, for example, a biological threshold

such as the rate of colonisation of new reefs by coral species as the temperature warms, or, if we imagine the curves to be for global sea-level rise, the rate of sea-level rise that corals can keep up with by upward growth. In the latter case, the value of this threshold is likely to vary with coral species or location, and with atmospheric [CO.sub.2] concentration, as discussed above. The evidence from Hopley and Kinsey (1988) discussed above suggests that, subject to additional localised stresses, a generalised threshold for the long-term drowning of coral reefs might be a local rate of sea-level rise of around 8 mm [yr.sup.-1], with decreased calcification rates due to increasing atmospheric [CO.sub.2] concentrations decreasing this threshold with time.

[Figure 10 ILLUSTRATION OMITTED]

Threshold B, on the other hand, is an absolute threshold. This might represent, for example, an absolute temperature above which coral bleaching is likely to occur. Again, this may be too simple, with other variables such as salinity or temperature playing a role.

We can use such diagrams to identify dates (which will vary with emission scenarios) at which the thresholds might be exceeded. Moreover, if we have established probability distributions for the critical variables (temperature or sea level), or combinations of variables, we could look at the risk of exceedence of the thresholds at any given date. Thus from Figure 10 we can see that the risk of reaching threshold B (hypothetically the onset of coral bleaching) is negligible before 2015, but becomes increasingly likely from 2015 to 2045, at which stage bleaching would be almost certain to occur. Superimposing the same threshold on a probability distribution for warming at 2030, such as that in Figure 9 for the north Australian coast, would enable the risk of bleaching at 2030 to be established. Further, by creating separate probability distributions for different emission scenarios, we could see the effect of different emissions on the probability of exceeding an impact threshold at any given date in the future. This approach is currently being developed further by Jones (in preparation) to look at the time-varying risk of exceedence of impact thresholds involving more than one climatic variable.

It is probable that a combination of (at least) three variables--temperature, aragonite saturation, and light levels will be needed to establish the broad threshold criteria for the survival of coral reefs (Kleypas, 1997; Kleypas and McManus, 1999; Gattuso et al., 1999b). Other climatic and environmental factors may well be important at particular locations (e.g., pollutants, wave energy, salinity).

### Integrated assessments of impacts and adaptation

If we are to address the purposes of sensitivity or risk analyses identified in the introduction, it is clear that much effort needs to be put into establishing multivariate thresholds for a range of impacts, and to attach some measure of importance or value to the impacts both locally and globally. This in itself will be a complex multi-disciplinary task, although some significant progress has been made, some of the main issues are already well addressed, and some critical parameters have been identified.

Another crucial need is to better estimate the time- and space-varying probability of reaching these thresholds. This requires a departure from the ideas of precise predictions, on the one hand, and of arbitrary scenarios on the other, to one of estimating probabilities which can be used in risk assessments. This will lead to less focus on extreme ranges of uncertainty, and more on the most probable outcomes, while paying due heed to less probable circumstances which in some cases might have more disastrous consequences.

The role of autonomous and planned adaptation in either changing the thresholds, or in mitigating the costs and preserving the existing values, needs to be explored. As other papers in this volume demonstrate, this requires a lot more research on the ecology of reefal communities. Planned adaptation measures and responses need to be placed in the full context of the reef communities, their ecosystem functions, and human values. Indeed, it must be understood that much human "development" in the vicinity of reefs is in a real sense maladaptation or short-sighted, achieving some narrow goal at the expense of the future health of the reef system. The utmost care will be needed to fully anticipate the consequences of human interference in reef communities before planned adaptation measures are implemented.

## CONCLUSIONS

Despite a large range of uncertainties, we can say something about several key factors likely to affect coral reefs:

- \* despite the Kyoto Protocol, unless there are unexpectedly large and rapid reductions in greenhouse gas emissions, actual [CO.sub.2] concentrations in the atmosphere are likely to reach double preindustrial values some time in the 2060s, leading to increased acidity of the surface layers of the ocean and a consequent reduction in calcification rates of coral;
- \* average sea surface temperatures in most coral reef areas will most probably be some 2 to 3[degrees]C higher in the late 21st century than in preindustrial times;
- \* while changes in average rainfall remain uncertain in reef areas, the magnitude of heavy rainfall and riverine run-off events is likely to increase;
- \* no large systematic changes in visible or ultraviolet radiation are expected in reef areas, although local changes due to changed cloud cover are possible;
- \* mean sea level is expected to rise by between 1 and 10 mm per year until well beyond 2100;
- \* evidence is mounting that tropical cyclones may increase in intensity by 10 to 20% by the 2070s, and they may travel further polewards as sea surface temperatures increase;
- \* synergistic effects due to a combination of climatic and other factors (such as pollution, turbidity and ocean chemistry) are likely to have the greatest impact.

We have thus made an important start in our effort to understand what reefs may need to adapt to, and (in other papers) how they might adapt. However, there is a great need for a greater focus on climate change simulation in reef regions at spatial scales appropriate to reefs, in order to

obtain more location-specific information on the above factors, and reliable information on other critical factors. The latter include particularly the behavior of ENSO in a warmer climate, tropical cyclones genesis location and numbers, regional variations in sea-level rise, location of the ITCZ and SPCZ, and changes in rainfall, runoff, and cloud cover. Without more quantitative and reliable information on these potential climatic changes, and a better understanding of the functioning of complex reef communities now, present and future adaptation and survival of reefs cannot be understood.

The reluctance of some international agencies to fund "research" is very shortsighted and damaging, in view of the inability of many small developing countries to mount effective climate change research programs by themselves. Funds for "capacity-building" and "adaptation measures" may well be wasted, or even used for inappropriate and counter-productive measures, unless guided by a thorough understanding of the key factors. Good answers can only come by addressing the right questions. Too often these are not being asked because of the lack of a fundamental understanding of the issues.

The focus must move away from prediction of extreme ranges of uncertainty, and focus instead on risk assessment. We need to know what are the more likely outcomes, and then express these in terms of the risk of critical or undesirable outcomes. Implicit in this is a set of values as to what is critical or unacceptable. This will include aesthetic and ecosystem values, but also some attempt to attach monetary values to reefs and their human and ecosystem services.

Finally, we must address the related questions as to whether autonomous adaptation can realistically meet the FCCC objective to "allow ecosystems to adapt naturally to climate change," given the present climate change projections. Will planned adaptation be essential for the survival of particular reef ecosystems (which often have great human value), or even for reefs in general? Is it possible, in the face of all the human and climatic stresses reef systems may face in the next century, for reefs in general, or particular reefs, to survive? The answers to these questions will not come from "capacity-building," but from well-focused research.

In summary:

- \* climate change scenarios relevant to impacts on coral reefs are emerging, but are still partial, too broadscale, and highly uncertain;
- \* there is thus a need for a greater focus on climate change research in tropical regions, at finer spatial scales, and on key variables such as ENSO, tropical cyclone behaviour and regional variations in sea-level rise;
- \* the focus should shift from single predictions, or extreme ranges of uncertainty, to risk assessment;
- \* thresholds critical to reef ecosystem health and survival should be identified;
- \* both autonomous and planned adaptations will be necessary to cope with multiple synergistic stresses;
- \* we do not know whether adaptation will be enough, for the survival of individual reef communities, or for reefs in general;
- \* "capacity-building" requires real knowledge of risk.

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