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COOPERATIVE RESEARCH CENTRE

POSITION ANALYSIS:

CO_2 emissions and climate change:

OCEAN IMPACTS AND ADAPTATION ISSUES

Australian Government
Department of the Environment, Water, Heritage and the Arts
Australian Antarctic Division

UTAS

CSIRO

Australian Government
Bureau of Meteorology

CRC
AUSTRALIA

Position Analysis: CO_2 and climate change: ocean impacts and adaptation issues.

PA02–080516

ISSN: 1835–7911

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1. introduction

Increased carbon dioxide (CO_2) emissions are causing acidification of Earth's oceans with potentially serious impacts, within the 21st century, for the sustainability and management of many marine and coastal ecosystems and fisheries. Ocean acidification and its impacts will be seen first in the Southern Ocean, providing early signals of what is likely to follow elsewhere. Progressive ocean acidification in temperate and tropical seas may have significant ramifications for human communities dependent on coastal resources in Australia, the Indian Ocean and South Pacific Regions.

The aim of this paper is threefold:

1. To inform the Australian government about recent developments in scientific research into ocean acidification;
2. To outline the likely impacts of increased carbon dioxide absorption on the world's oceans, in particular the Southern Ocean; and
3. To identify issues for consideration in policy development.

Photo: Sandy Zicus

2. the science of ocean acidification

Human-induced CO_2 emissions have arisen mainly from fossil fuel combustion, land-use practices and concrete production during and since the industrial revolution.

These emissions first enter the atmosphere, but a large proportion of them are then absorbed into the ocean by physical and biological processes that are normal parts of the natural carbon cycle. The result is more CO_2 dissolved in the world's oceans. The term 'ocean acidification' refers to the fact that the CO_2 forms a weak acid (carbonic acid) in water, making the ocean more acidic. The basic chemistry is as follows: the ocean is a weakly-alkaline solution (with a pH of ~ 8.1), but this extra CO_2 changes the carbonate chemistry of the surface ocean and drives the ocean pH lower, meaning that the ocean is becoming more acidic (less alkaline).

This process of ocean acidification is already underway and discernible (Feely *et al.,* 2004), and has lowered the ocean's pH from its pre-industrial state.

The level of atmospheric CO_2 is now higher than at any time in at least the past 650,000 years, and probably has not been as high as present levels for 20 million years.

The current rate of increase of CO_2 in the atmosphere (~1.1 parts per million per year) is one hundred times greater than the most rapid increases during major climate changes over the last 650,000 years, and probably much longer. Approximately half the fossil fuel CO_2 emitted by man has now dissolved into the ocean.

Atmospheric CO_2 levels are expected to reach about double pre-industrial levels within this century, resulting in a pH reduction (acidification) of the oceans by about three times that experienced during the last major rise in atmospheric CO_2 at the end of the last glacial period 15,000 years ago (see Figure 1).

Ocean acidification is a *direct* consequence of CO_2 emissions, so differs from the overall challenge posed by global warming in that the inevitable and inexorable rise of dissolved CO_2 in the ocean will continue independently of whether the atmosphere is warming.

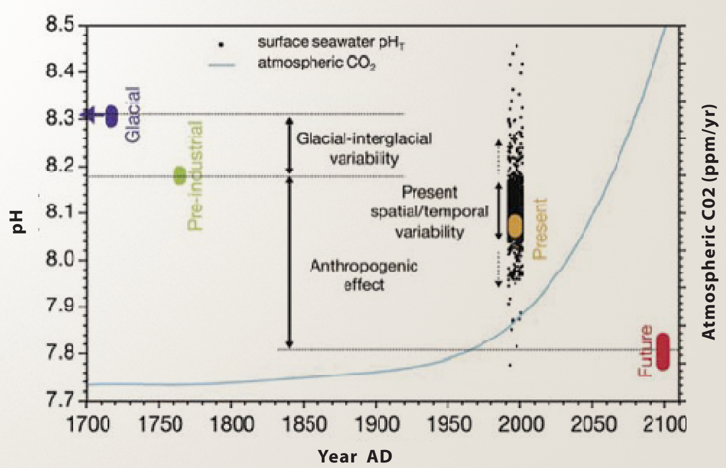
Specifically, the rate and extent of CO_2-driven acidification depends mainly on the rate of CO_2 input into the atmosphere and not on the behaviour of CO_2 as a greenhouse gas.

The main questions about the CO_2-driven acidification process concern the rate and distribution of the chemical changes resulting from increased CO_2 absorption into the oceans.

Though uncertainties remain, there are already reasonably accurate estimates of the penetration of anthropogenic CO_2 into the ocean (Sabine *et al.*, 2004; Feely *et al.*, 2004). Because the processes by which the ocean buffers the CO_2 input have time-scales ranging from decades to millennia, a rapid reversal of this process is unlikely even with immediate and radical cuts in anthropogenic CO_2 emissions[1].

Figure 1.
Scale of ocean pH change.

Figure 1 shows the predicted ocean pH (left axis) in 2100 (red bar at right) compared to the current value (orange dot, centre), the pre-industrial level (green dot, left) and that at the peak of the last ice age (blue dot, left). The difference between the blue and green dots is the result of natural variation between glacial and inter-glacial conditions. The difference between the pre-industrial (green dot) and present (orange dot) and future (red bar) indicates the net effects of anthropogenic CO_2 emissions to date and during this century. Also shown is the current spatial and temporal variation in ocean pH (black dots around current average) and the trajectory (curved blue line) of total concentration of CO_2 in the atmosphere (right axis) from 1700 to 2100 AD. The upward curve of the line is mostly due to anthropogenic CO_2 emissions. *Source:*



3. oceanic impacts

The pre-industrial pH of the ocean (~ 8.1) was the result of a long-term balance among carbonate shell formation by marine organisms, supply of dissolved bicarbonate by rivers, deposition of carbonate sediments on the seabed, and dissolution of carbonate sediments (Ridgwell and Zeebe, 2005). The input of CO_2 to the ocean is changing this balance, driving ocean pH lower and creating more acidic (less alkaline) oceans.

CO_2 emissions may have both direct and indirect impacts on the ocean. An example of an indirect impact is ocean anoxia[2] associated with ocean warming and changes in its circulation.

The main short-term response to increased CO_2 absorption in the ocean is a shift in the proportion of bicarbonate and carbonate ions. Specifically, more CO_2 in the ocean is lowering the availability of dissolved carbonate ions to organisms. It is this carbonate that calcifying organisms use to precipitate their shells.

The potential impact of acidification was recognised and began to be quantified with a series of papers which forecast the chemical impact of future CO_2 emissions on ocean pH (Caldeira and Wickett, 2003) and on the concentrations of the chemical constituents necessary for calcification by corals (Kleypas *et al.*, 1999) and other marine organisms (Feely *et al.*, 2004; Orr *et al.*, 2005).

Reviews of the long-term processes responsible for ocean acidification and its potential ecological impacts have been carried out by the British Royal Society (Raven *et al.*, 2005), the German Advisory Council on Global Change (Schubert *et al.*, 2006) and jointly by the US National Science Foundation (NSF), National Oceanic and Atmospheric Administration (NOAA), and the US Geological Survey (USGS) (Kleypas *et al.*, 2006).

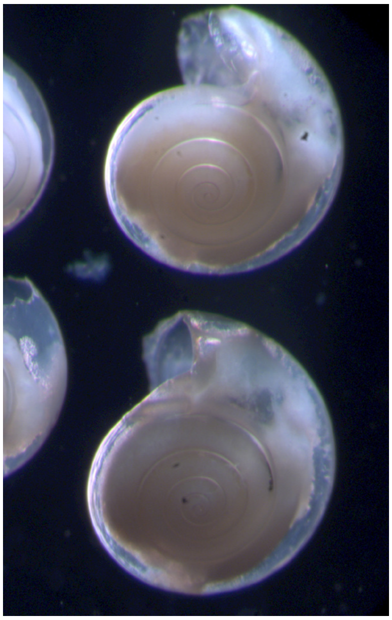


Photo: Russell Hopcroft

1 Ocean acidification has some similarities with and some differences from, the problem of 'acid rain' that affected Northern Hemisphere aquatic ecosystems in the 1970s and 1980s. That acid derived from the SO_2 emissions from coal burning, which formed the relatively strong sulphurous acid on dissolution in water. Acidification from CO_2 differs in being less intense locally but more widespread globally. Another major difference is that CO_2 is far more persistent, remaining in the atmosphere hundreds of years rather than just months for SO_2. The acid rain problem has been greatly reduced by a combination of improved emissions standards and compliance with international legal regimes that incorporate these internationally agreed emissions standards. However emissions standards have not yet been negotiated nor implemented for CO_2.

2 Ocean anoxia arises from the 'loading' of the ocean (or any body of water) with organic matter, whose decomposition by respiration consumes oxygen. In conditions of strong stratification associated with surface warming, the oxygen consumed in subsurface waters is not replaced, as exchange with the atmosphere is limited (eg Sarmiento *et al.*, 1988). There are relatively few anoxic regions of the modern ocean. Examples include the Santa Barbara Basin, the Benguela Current region off Namibia, and the Northern Arabian Sea.

3. oceanic impacts

The impact of ocean acidification is projected to vary regionally with varying rates of CO_2 uptake from the atmosphere and pre-existing variations in the chemical state of seawater.

Because it is a cold mass of water, the Southern Ocean contains a disproportionate amount of the oceanic inventory of anthropogenic CO_2 compared with other, warmer oceans. It is therefore already chemically closer to carbonate minerals' saturation points than other oceans.

Figure 2.
The spread of acidification into the ocean.

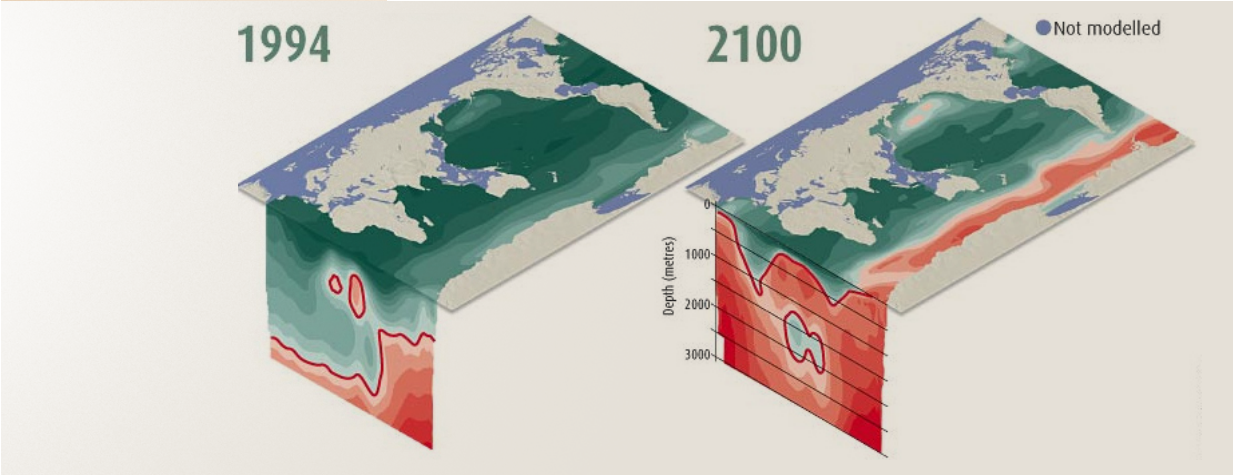
The spread of acidification of the earth's oceans from 1994 (left) to 2100 (right). Green areas indicate waters supersaturated with aragonite carbonate and favouring shell formation, with darker colour indicating more favourable conditions. Red areas are those where waters are under-saturated in aragonite and so hostile to shell formation by marine organisms, with darker colour indicating greater under-saturation. *Source: Henderson (2006), after Orr et al. (2005).*

Biogeochemical model projections indicate that the Antarctic polar waters will be the first to experience carbonate ion concentrations low enough that aragonite, one form of calcium carbonate, will no longer be able to be precipitated by shell-forming organisms (Figure 2; Orr *et al.*, 2005).

The Southern Ocean is a biogeochemical 'harbinger' for the impacts of acidification that will spread throughout the global ocean.

Australia's Antarctic interests, including its large Antarctic territorial claim, make this a particularly sensitive national issue. Ocean acidification thus can be viewed as an impact 'advancing from the south'.

Acidification will have impacts on key Australian marine ecosystems such as those of the Southern Ocean, marine protected areas on the southern margins of the Australian continent (the Great Australian Bight and Tasmanian seamounts) and, eventually the Great Barrier Reef.



3. oceanic impacts

Ecological Effects

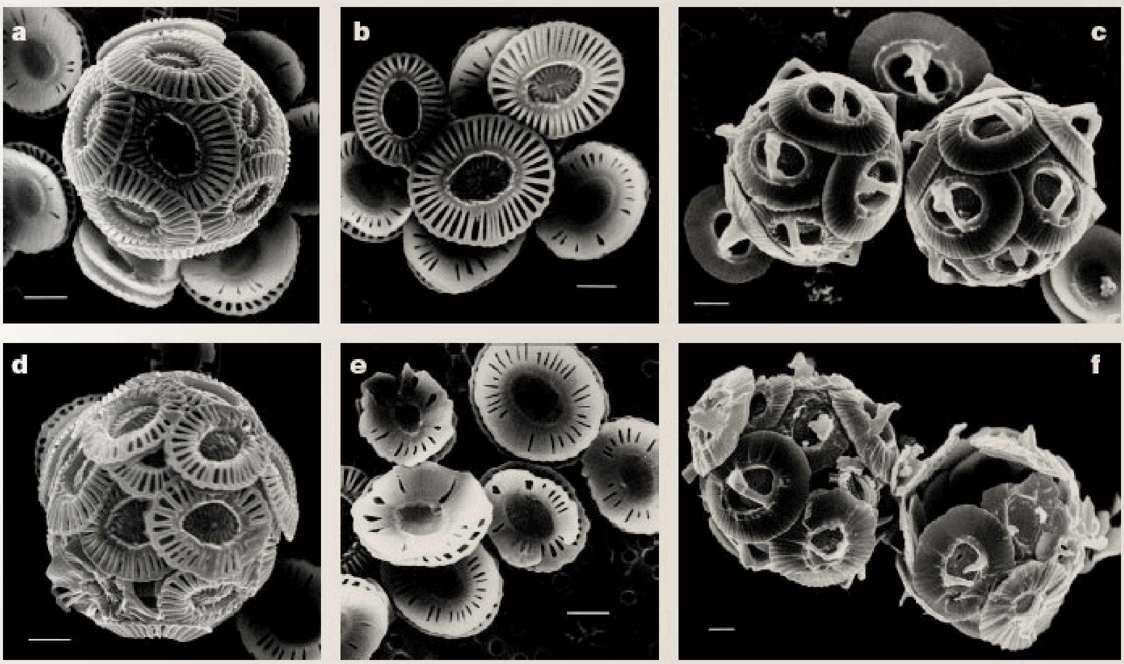
The ecological effects of changing ocean carbonate chemistry are uncertain due to the complexity of marine ecosystems. Research so far has focussed on the impact of acidification on calcifying organisms, however the actual impacts of acidification may range across a broad spectrum of physiological and ecological processes. Expected effects include reductions in the calcification rates of marine organisms such as cocolithophorids, corals, pteropods and planktonic foraminifera. Coccolithophorids are a key microalgal primary producer in ocean ecosystems.

In Figure 3, panel a-c (top images) show organisms grown at a CO_2 level of 300 parts per million (ppm) (just slightly above pre-industrial levels), and panels d-f (bottom images) show the same species grown at 780–850 ppm. At high CO_2 levels the algae show lower calcification rates and malformed calcite shells.

Other ecological effects of ocean acidification may include interference in the respiration of fish (Ishimatsu *et al.*, 2005), effects on larval development of marine organisms and changes in the solubility of both nutrients and toxins. These impacts are still poorly understood and are a priority area for acidification research.

Figure 3.
The impacts of higher-than-present CO_2 on the calcification of coccolithophorids.

Shells in the top three images were grown at slightly above pre-industrial levels of CO_2 and have normal shells; those in the bottom three images were grown around three-times pre-industrial levels and are diminished or malformed. *Source: Riebesell et al. (2000).*



4. questions and uncertainties

There are significant uncertainties surrounding ocean acidification including the rate, variability and extent of such chemical changes in the ocean.

While small-scale experiments and modelling provide important information, further scientific observations on natural systems, coupled with further model development, will be important to narrow these uncertainties. Because impacts of changing ocean chemistry are expected to be obvious first in the Southern Ocean, targeted research in that region is likely to be most immediately informative.

A key problem is to anticipate the effects of global ocean acidification on marine environments, including those of the Southern Ocean. Monitoring acidification is at an early stage so that it is not clear what impacts, deleterious or beneficial, have already occurred. Crucial unanswered scientific questions include: How will ocean acidification affect marine ecosystems? How will calcification rates in plankton carbonate shell producers be altered? What will impacts on marine phytoplankton mean for ocean uptake of CO_2? What effects will changes in planktonic production have on higher trophic levels including fish? What are the thresholds in carbonate mineral saturation state beyond which calcifiers like coral can no longer produce carbonate? What are the expected impacts on fisheries and aquaculture?

A major 'wildcard' among these scientific questions lies in uncertainty about the response of individual organisms to the impacts of ocean acidification.

Many species have taken millennia to evolve and it is unknown whether they can (or will), be able to adapt to the relatively rapid rate of ocean acidification – in the order of decades, not millennia.

Photo: Russell Hopcroft

5. science–policy issues

Concern about ocean acidification arose originally in discussions about the ecological impacts of proposed deep-ocean carbon sequestration by direct injection of carbon to deep-ocean waters (Brewer *et al.*, 1999; Seibel and Walsh, 2001).

While the idea of ocean 'disposal' of CO_2 is not new – humans have been inadvertently carrying out such sequestration for about 200 years via CO_2 emissions into the atmosphere – the notion of active sequestration is relatively recent.

Ocean acidification has recently emerged as an international and a national environmental issue, particularly in scientific, political, policy and media circles, including in media such as *The New Yorker* (Kolbert, 2006). In the USA, ocean acidification has entered the political debate formally with the introduction of a US Senate bill to establish an ocean acidification research and monitoring plan. This bill would appropriate US$30 million for an ocean acidification program with the US National Oceanographic and Atmospheric Administration[2]. Ocean acidification has yet to assume the high-level public profile within Australia that it occupies in the USA.

With some of Australia's highest-profile natural heritage sites at significant risk ecologically and economically, however, both federal and state governments should be alerted to the likely impacts of ocean acidification on assets such as the Great Barrier Reef and the marine ecosystems of the Southern Ocean. Policy responses to ocean acidification will have to include forecasting and adaptation strategies.

Impacts

The issue of ocean acidification poses important challenges for government. The long-term nature of this problem, together with increasing public concern about climate-related changes in the world's oceans, emphasises the importance of strategic scientific research and its integration with 'real-time' policy applications.

The impact of ocean acidification has implications for marine environments, fisheries and aquaculture. Australia has a number of important environmental assets at risk from the impacts of the acidification process. The best-known of these is the Great Barrier Reef. The vulnerability of corals to elevated CO_2 has been estimated in laboratory studies (Langdon, 2000) but remains untested in natural field conditions.

The response of other calcifying organisms that underpin the stability and biodiversity of benthic habitats such as those of the Great Barrier Reef, including coralline algae and tube-worms, is unknown. A number of the key species that make up the Great Barrier Reef ecosystem secrete mineral forms of calcium carbonate that differ from the aragonite making up the corals. The growth rates of these organisms may be affected at lower levels of elevated CO_2 than those affecting corals (Morse *et al.*, 2006). As well, other environmental impacts such as increased temperature and nutrient loading, may have synergistic effects on the growth of corals and other calcifiers (Hoegh-Guldberg, 2005).

While Australia has a range of ocean monitoring programs in place, including observation programs in the Southern Ocean, monitoring acidification is at an early stage. In the short-term (the next few decades), developing or extending existing monitoring programs (those established on the Great Barrier Reef or in development in the Southern Ocean) will provide important data in modelling the effects of acidification.

[2] A bill to establish an interagency committee to develop an ocean acidification research and monitoring plan and to establish an ocean acidification program within the National Oceanic and Atmospheric Administration, United States Senate Bill S.1581. URL: http://www.govtrack.us/congress/bill.xpd?bill=s110-1581.

5. science–policy issues

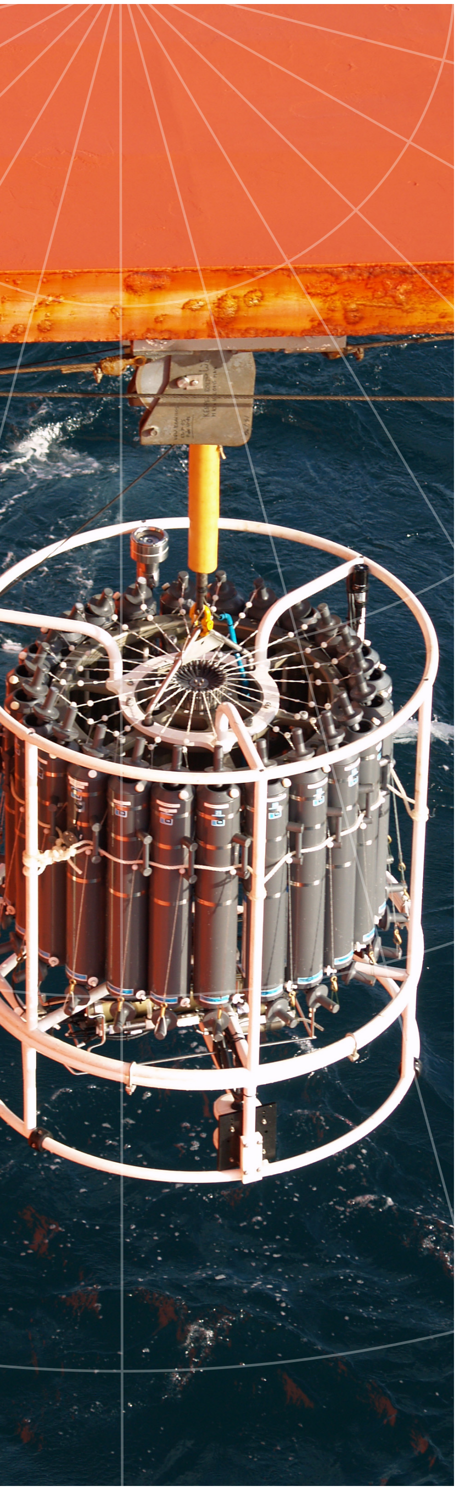


Photo: Andrew Moy

Another key vulnerability for Australia's Great Barrier Reef and for low-lying island nations in the Pacific and Indian Oceans (Kiribati, Maldives) is that ocean acidification may exacerbate other climate change- and weather-related impacts on coral reefs.

For example, if ocean acidification weakens the structure of reef-forming corals and algae, tropical systems will be more vulnerable to physical impacts from storms and cyclones. These impacts will also directly affect important commercial, recreational or subsistence reef fisheries where the target species depend on reef habitats.

Australian waters also include poorly understood calcifying communities such as bryozoan reefs in the Great Australian Bight and deep-water corals occupying seamounts off Tasmania. The importance of these communities to Australian fisheries is unknown.

However, the organisms likely to be affected are key components of the benthic habitats on which many fisheries in Australian waters are dependent. Ocean acidification will also affect gastropods such as abalone and bivalves including oysters (meat and pearls) and mussels. These species are important to aquaculture industries in Australia and the South Pacific Region.

In the medium- to long-term (the next century), these changes in ocean chemistry are likely to have an impact on fisheries and aquaculture management and practices. While the exact form of such impacts is not easily predicted, it is likely that existing aquaculture operations will be affected both in terms of the species produced and areas suitable for production. At the same time, however, other environmental impacts associated with climate change, including increased water temperatures and increased frequency and severity of extreme events, are also predicted to have an impact on Australian and Pacific region aquaculture.

5. science–policy issues

Mitigation measures

Mitigation is less likely to be a realistic option than developing adaptation strategies and action plans at regional, national and local levels in Australia and in the Pacific and Indian Ocean regions. There are, as yet, few practical engineering solutions to ocean acidification, though the deliberate dissolution of limestone has been proposed as a means of buffering CO_2 in the ocean (Caldeira and Rau, 2000). Possible engineering solutions (at least locally) including adding buffering agents such as ground limestone to waters overlying reefs, are not without their problems. For example, the quantities of buffering agents required are large – over 13 billion tonnes of limestone per year would be required to buffer the current annual emissions of CO_2. The environmental costs of such mitigation measures are highly uncertain and unlike terrestrial applications (such as liming lakes), their effects cannot be contained to a particular locale.

The implications of any mitigation measures will need to be thoroughly examined as they will involve manipulating marine ecosystems.

This is currently precluded under relevant Australian legislation, and a significant issue, apart from any environmental considerations, is listing the mitigation agents – whether permitted (white-listed) or prohibited (black-listed). Any mitigation or amelioration measures would need to be assessed for the extent to which they can be adequately addressed under existing environmental impact assessment processes or existing legislative requirements. In the long-term, amending Australian legislation or regulations may need to be considered.

One of the main difficulties in estimating mitigation is the lag between the emission of fossil-fuel carbon and its uptake by the ocean and other reservoirs. Because the mechanisms in the ocean and the biosphere which will act to neutralise and sequester anthropogenic CO_2 are far slower than the rate of input, the fossil-fuel CO_2 already added will remain in the atmosphere and continue to be absorbed by the ocean for millennia (Archer, 2005). In addition, as the pH restoration of the ocean is controlled by the dissolution of calcium carbonate sediments on the seabed, the recovery from ocean acidification also has a time scale of thousands of years (Archer *et al.* 1997).

Ongoing research on the impacts of mitigation measures on marine ecosystems needs to be undertaken alongside the legal and international relations aspects.

5. science–policy issues

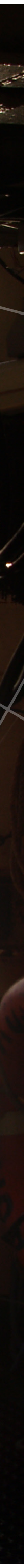
Adaptation Strategies and action plans

Some coastal communities in Australia, and countries in the South Pacific Region including Samoa and Kiribati, are developing climate change adaptation strategies and action plans to address the impacts of sea-level rise and climate change. Strategies for ocean acidification also need to be factored into these plans. In particular, the risks associated with the likely effects of increased acidification on coral reef structures and marine ecosystems need to be assessed and ongoing monitoring systems need to be put in place.

In this context, ocean acidification has implications for Australia's international aid programs. For example, changes in ocean acidification have significant implications for local communities and economies that rely on fisheries and aquaculture both as domestic food resources and as products for export. Risk assessments of the likely ecological, economic and social impacts of acidification will be required for communities and governments to plan adaptation initiatives that will be appropriate to the countries and communities likely to be affected.

Adaptive management is another possible strategy in some areas. As the locations of optimal resource areas change, so fishing and aquaculture operations may have to change. This may have significant implications for existing fisheries, for aquaculture rights and for management arrangements and it raises a number of questions for governments to address including: Will holders of fishing and aquaculture leases and/or licences seek compensation for losses incurred, or is this addressed by sovereign risk?

Photo: Andrew Moy



6. conclusion

Recent science has demonstrated that increasing levels of atmospheric CO_2 are leading to ocean acidification. Impacts of acidification will be seen first in the Southern Ocean, providing insights to what is to be expected elsewhere in the future. The rate and magnitude of these impacts remain uncertain.

Ultimately, acidification is expected to have important consequences for marine ecosystems and the human communities that depend on them both in Australia and in neighbouring regions. The feasibility, effectiveness or impacts of potential mitigation or adaptation strategies to respond to ocean acidification are also uncertain.

Analysis of the scientific and policy implications of increasing ocean acidification will be essential to properly inform 'real-time' policy options for responding to this looming problem. 'Science-policy partnerships' among scientists, decision makers and communities in Australia, the South Pacific and the Indian Ocean regions would facilitate greater understanding of acidification and assist communities to identify appropriate local, national and international responses to likely impacts.

Photo: Andrew Moy

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On-line resources:

The Ocean Acidification Network. http://ocean-acidification.net/

Ocean Acidification at the World Ocean Observatory website: http://www.thew2o.net/events/oceans/oa.php