

# Marine Climate Change in Australia

## Impacts and Adaptation Responses 2012 REPORT CARD

### Ocean acidification

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# Ocean acidification

## Introduction

### Context and purpose

Increasing atmospheric CO<sub>2</sub> concentration is causing increased absorption of CO<sub>2</sub> by the world's oceans, in turn driving a decline in seawater pH and changes in ocean carbonate chemistry that are collectively referred to as **ocean acidification**. Evidence is accumulating to suggest ocean acidification may directly or indirectly affect many marine organisms and ecosystems, some of which may also hold significant social and economic value to the Australian community.

This report card aims to provide a brief overview of the current state of scientific knowledge regarding the process of ocean acidification; current and future projected levels of ocean acidification; and, observed and projected impacts of current and future predicted levels of ocean acidification on marine organisms and ecosystems in the region. This Report Card also briefly discusses potential social and economic implications, policy challenges, and the key knowledge gaps needing to be addressed.

### What is ocean acidification?

Anthropogenic CO<sub>2</sub> emissions arising from fossil-fuel combustion, land-use practices, and concrete production during and since the industrial revolution first enter the atmosphere, but a large proportion of are absorbed into the ocean by physical and biological processes that are normal parts of the natural carbon cycle. These emissions have resulted in a ~40% increase in atmospheric CO<sub>2</sub> concentrations over pre-industrial levels [Tans and Keeling, 2011]. Over the same period, the ocean has absorbed approximately 30%-50% of these emissions [Sabine et al., 2004; Sabine and Tanhua, 2010]. Although the absorption of anthropogenic CO<sub>2</sub> by the ocean has provided a degree of buffering against global warming (which results largely from increased CO<sub>2</sub> in the atmosphere), the increase in dissolved CO<sub>2</sub> is accompanied by chemical reactions that increase oceanic hydrogen ion concentrations (thus reducing seawater pH) and bicarbonate ion concentrations while reducing carbonate ion concentrations.

The result is more CO<sub>2</sub> dissolved in the world's oceans. Seawater is a weakly-alkaline solution (with a pH of ~ 8.1), but this extra CO<sub>2</sub> changes the carbonate chemistry of the surface ocean, driving ocean pH and carbonate ion concentrations lower. While the relative acidity or alkalinity of seawater (typically measured as pH) shows significant spatial and temporal variation throughout the world's oceans, seawater is on average a weakly-alkaline solution (with a mean pH of ~ 8.1). Ocean acidification is estimated to have lowered the mean pH of the ocean from its pre-industrial state by about 0.1 pH units [Friedrich et al., 2012]. The declining trend in pH has been verified in recent decades by measurements e.g. [Byrne et al., 2010; Doney et al., 2009].

The process of ocean acidification is already underway and discernible in the ocean [Feely et al., 2004]. By the end of this century pH levels are likely to drop 0.2 – 0.3 units below pre-industrial pH. The level of atmospheric CO<sub>2</sub> 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 approximately 4-5 million years [Hönisch et al., 2012; Pagani et al., 2010]. The current rate of increase of CO<sub>2</sub> in the atmosphere is one hundred times greater than the most rapid increases during major climate changes over the last 650,000 years, and the concomitant rate of carbonate chemistry change in the ocean is similarly rapid [Friedrich et al., 2012; Lüthi et al., 2008; Midorikawa et al., 2012].

Nearly half the fossil-fuel CO<sub>2</sub> emitted to date has now dissolved into the ocean [Le Quéré et al., 2009; Sabine et al., 2004].

CO<sub>2</sub>- driven acidification, in addition to lowering seawater pH, shifts the proportion of dissolved carbon dioxide away from carbonate ion and to bicarbonate ion, and thus towards lower saturation states for carbonate mineral. Calcium carbonate precipitation at a decreased saturation state requires higher energetic demands from shell-making organisms.

### **Why is ocean acidification a concern?**

The marine environment is home to a vast and diverse range of organisms and ecosystems, all of which will directly or indirectly experience, to a greater or lesser degree, changes in ocean chemistry associated with ocean acidification. For many marine organisms, marine carbonate chemistry and pH are known to play important roles in key physiological processes (e.g. calcification in corals and shellfish, acid/base balance, fertilisation etc) that ultimately influence their behaviour, growth, development and/or survival. Some research suggests that ocean acidification has already begun to have detectable impacts on some biological processes.

Most conclusions about biological responses to ocean acidification in Australian waters come from laboratory manipulations rather than in situ observations. However there is observational data documenting already-underway changes in calcification in Southern Ocean zooplankton [Moy et al., 2009; Roberts et al., 2011] and in Great Barrier Reef corals [Cooper et al., 2008; De'ath et al., 2009]. Though unambiguous attribution of these observed trends to acidification is still uncertain, they suggest acidification may have already begun to have detectable impacts on biological processes.

Similarly, a range of physiological processes are sensitive to pH itself. Changing pH also influences other important aspects of seawater chemistry, such as the availability of nitrogen and iron (both necessary for marine plant production) [Shi et al., 2010].

Given that a significant proportion of the global (including Australian) human population is directly or indirectly reliant on the ecosystem services provided by the ocean (e.g. for food security, employment, tourism), many governments are becoming increasingly concerned with understanding the likely ecological, economic and social implications of ocean acidification

There are a number of key questions that must be addressed to inform decisions regarding the management of, and response to, this issue in the short and long term:

1. What is the current degree of acidification and what level is it predicted to reach in the short, medium and long term, a range of anticipated global carbon emission scenarios?
2. Which organisms and ecosystems have been or will be impacted by ocean acidification? How soon will impacts manifest themselves and are any species or ecosystems likely to benefit?
3. How will ocean acidification interact with other ecosystem stressors (e.g. pollution, overfishing, ocean warming, hypoxia, etc.)

## Ocean acidification

4. What capacity might organisms have to adapt to ocean acidification (i.e. via natural selection of resistant individuals over relevant timeframes)?
5. What are the social and economic implications of ocean acidification impacts?
6. What policy response is required?

The level of research into and understanding of ocean acidification and its potential biological impacts is growing rapidly. The following sections summarise the current state of scientific knowledge pertaining to observed and predicted changes in ocean chemistry and biological processes resulting from ocean acidification, with special emphasis on studies relevant to the Australasian region. This review is intended to highlight knowledge gaps and facilitate discussion of policy implications and challenges (including social and economic implications).

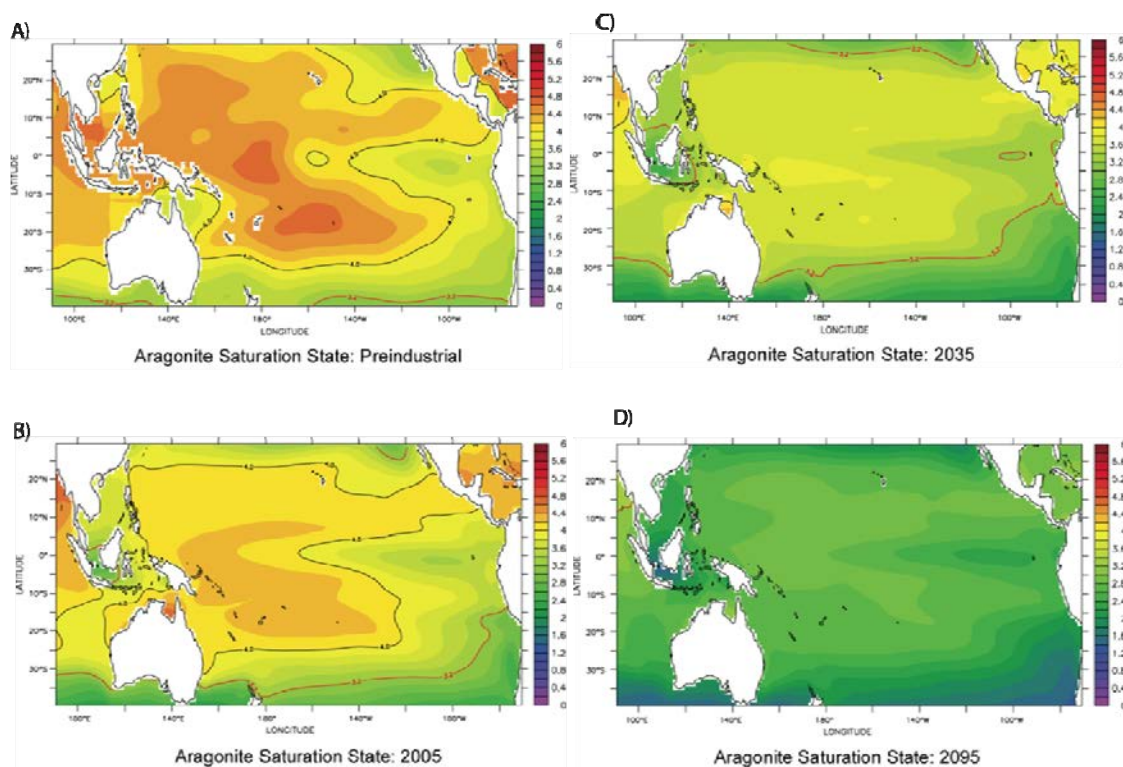


Figure 1. Annual mean aragonite saturation state in the surface water for: a) 1800; b) 2005; c) 2035; d) 2095. For the future years the IS92a atmospheric CO<sub>2</sub> concentrations is used along with the CSIRO Mk3.5 climate projection to determine project the aragonite saturation state.

Major scientific knowledge gaps in the physical response lie in several aspects of the physical, biological, and ecological implications of ocean acidification. One area of gap is in projecting the spatial and temporal variability in the progression of acidification. In particular there is a critical need for regional and local-scale data on carbonate chemistry variability. Another major class of knowledge gaps concerns the vulnerability of different organisms and ecosystems. The major scientific knowledge gaps in biological and ecological responses lie in understanding inter-specific and intra-specific differences in response to acidification (“winners” versus “losers”) or the ability to internally regulate pH [McCulloch et al., 2012a; McCulloch et al., 2012b], the potential evolutionary adaptation of organisms to acidification [Parker et

al., 2012; Sunday et al., 2011], and in the implications for the structure of ecosystems [Hughen et al., 2004; Hughes et al., 2010; Pandolfi et al., 2011]. Similarly, though much research has focused on marine calcifiers, the impact of shifts in carbonate chemistry on microbial communities and processes is still little understood e.g. [Bowler et al., 2009; Tortell et al., 1997; Witt et al., 2011]

### Observed Impacts

#### Chemical changes to the oceans

**High Confidence.** The pH of surface oceans has dropped by 0.1 units since the industrial revolution [Feely et al., 2004; Feely et al., 2009]. The carbonate mineral saturation state for calcite and aragonite show decade-scale downward trends [DeVries and Primeau, 2009; Doney et al., 2009; Feely et al., 2012; Matear and McNeil, 2003; Matear and Lenton, 2008; McNeil and Matear, 2008]. Historical pH drops in seawater pH have been inferred using boron isotope proxies in coral archives [Pelejero et al., 2005; Pelejero et al., 2010; Wei et al., 2009].

#### Biological changes to the oceans

**Medium confidence.** Calcification rates in Southern Ocean calcareous zooplankton (foraminifera) have dropped 30-35 % since the pre-industrial times [Moy et al., 2009]. Great Barrier Reef corals have reduced calcification rates [De'ath et al., 2009]. Though attribution to ocean acidification alone is unclear (increased sediment runoff and thermal stress are the other likely causes), recent declines in GBR-wide coral calcification rates are unprecedented in at least the past 400 years. It is nevertheless clear that changes in the marine environment together with more frequent coral bleaching are reducing coral growth rates. Evidence is emerging of similar declines from other coral reef regions [Tanzil et al., 2009] although some coral reefs distal from terrestrial impacts show greater rates of calcification [Cooper et al., 2012] consistent with the positive enhancement of warming on calcification e.g. [McCulloch et al., 2012a]. Lightly calcified coccolithophores have shifted ranges poleward in recent years. Though attribution to ocean acidification is unclear, the pattern is consistent with the expected impact [Cubillos et al., 2007].

**Low confidence.** Calcification in pteropods in the Southern Ocean [Roberts et al., 2011] and tropical waters [Roger et al., 2012] has decreased on decadal time scales.

### Potential impacts by the 2030s and 2100s

#### Chemical changes to the oceans

**High Confidence.** The pH of surface oceans will drop by 0.2 – 0.3 units by ~ 2100). The carbonate mineral saturation states for calcite and aragonite will continue their decade-scale downward trends [Matear and Lenton, 2008]. In areas of high seasonal variability in carbonate chemistry, such as the high-latitude Southern Ocean, aragonite saturation thresholds may be crossed in winter by ~ 2040 [McNeil and Matear, 2008; McNeil et al., 2011].

**Medium Confidence.** The entire Southern Ocean surface (south of the current Polar Front Zone) will be undersaturated for aragonite by ~ 2100 [Orr et al., 2005]. Tropical

## Ocean acidification

aragonite saturation states will decrease to a level that will prevent optimal coral growth [Kleypas et al., 1999; Orr et al., 2005; Veron et al., 2009]. Aragonite saturation horizons will shoal, especially in the Antarctic and Australian southern margins, threatening a wide range of benthic calcifiers (see below).

**Low confidence.** pH changes in coastal systems have mirrored changes in the open ocean. There are few long-term records of the CO<sub>2</sub>-carbonate system in shallow coastal systems. In shallow coastal systems there are a number of processes that produce and consume alkalinity that can potentially buffer or enhance the effect of ocean acidification. These include the dissolution of carbonate minerals, sediment denitrification, and reduced sulphur burial. Coastal systems also receive river and groundwater inputs of alkalinity. Alkalinity sinks in coastal systems include precipitation of carbonate minerals, oxidation of reduced sulphides, and coupled nitrogen fixation and aerobic respiration.

### Biological changes to the oceans

**Medium confidence.** Calcification rates in Southern Ocean calcareous zooplankton (foraminifera) are likely to continue to decline [Moy et al., 2009] and impacts on pteropods are likely to emerge [Fabry et al., 2008]. Many taxa of calcifiers especially that are unable to internally manipulate their pH (eg coralline algae and some foraminifera) will experience reduced calcification rates [Anthony et al., 2008; Anthony et al., 2011b; De'ath et al., 2009]. Coral growth is likely to be affected by multiple impacts of ocean warming, bleaching and acidification [Erez et al., 2011; Hobday and Lough, 2011; Hoegh-Guldberg, 2005; Hoegh-Guldberg et al., 2007; Lough and Cooper, 2011; Lough and Hobday, 2011; Silverman et al., 2007; Silverman et al., 2009]. However, corals show a diversity of responses to acidification, and overall responses or reef ecosystems are likely to be complex. In particular some marine organisms may have evolutionary time scales short enough to adapt to acidification on decadal to centennial time scales e.g. [Sunday et al., 2011].

Many mid- and high-latitude benthic calcifiers such as deep-water and cold-water corals [Guinotte et al., 2006; Maier et al., 2009], coralline algae e.g. [Martin et al., 2008; Martin and Gattuso, 2009; Russell et al., 2009; Russell et al., 2011b], bryozoans [Smith, 2009; Smith and Lawton, 2010] and other benthic calcifiers [McClintock et al., 2009] are likely to show the effects of increased dissolution on their exposed carbonate skeletons as aragonite saturation horizons shoal [McCulloch et al., 2012b]. The effects on calcification will be variable, dependent on species specific internal processes to modulate pH regulation and likely enhancement of calcification from warming of cold-water environments [McCulloch et al., 2012a].

Economically important taxa such as shellfish may show reduced growth and/or calcification [Barton et al., 2012].

Ecosystems will show signs of restructuring as changes to ecosystem services like calcification alter benthic substrata, and to the extent non-calcifiers are advantaged.

**Low confidence.** Possible reduction in fertilisation in some marine invertebrates [Havenhand et al., 2008; Havenhand and Schlegel, 2009; Parker et al., 2009; Parker et

al., 2012], but not others [Byrne, 2012]. Some reef fishes may experience impaired olfactory-based navigation under lower pH, hindering their ability to find suitable habitats [Munday et al., 2009b].

Overall responses of fish taxa may be highly varied and thus difficult to simply predict, but have significant implications for economically-important ecosystems and fisheries. Experimental evidence available to date suggests ocean acidification is not likely to have significant direct effects on the growth, development and survival of most adult fish taxa. However elevated CO<sub>2</sub> may affect sensory systems and behaviour. Recruitment adult populations would decline if increased mortality of larvae and juveniles results from acidification. Reduced aerobic capacity in some fish could exacerbate climate change impacts.

**Low confidence.** pH changes in coastal systems will mirror predicted changes in the open ocean. Shallow coastal systems have a number of alkalinity sources and sinks that may potentially buffer against, or enhance, ocean acidification (see above). In addition, other stressors such as eutrophication and hypoxia will also interact with ocean acidification to modify its effect in shallow coastal systems.

### Adaptation Responses

The likely peak of atmospheric carbon dioxide levels well above present concentrations, even with emissions-reduction measures, means ocean acidification impacts will be inevitable and marine ecosystem management strategies (e.g. marine protected areas) will have to factor in some acidification impacts.

### Knowledge Gaps

There exist a number of important scientific knowledge gaps pertaining to the response of physical and biological systems to ocean acidification. These gaps also hinder our ability to understand the social and economic implications and hinder the capacity of decision makers to develop appropriate policy responses. Key knowledge gaps include:

1. **Physical/chemical responses:** There is a lack of understanding of future fine scale spatial and temporal variability in the progress of acidification. There is a critical need for regional and local-scale data on carbonate chemistry variability, such as large-amplitude tidal-cycle changes in carbonate chemistry, pH, and net calcification [Hofmann et al., 2011; Santos et al., 2011; Shaw et al., 2012].
2. **Biological/ecological responses:** There is a lack of understanding of:
  - a. Inter-specific and intra-specific differences in response to acidification (“winners” versus “losers”). Much research has focused on marine calcifiers, however the impact of shifts in carbonate chemistry on other key ecosystem components, such as microbial communities and processes, is still little understood e.g. [Bowler et al., 2009; Tortell et al., 1997]

## Ocean acidification

- b. The potential for organisms to adapt (via natural selection for more resistant individuals) to changes in ocean chemistry over relatively short time frames [Parker et al., 2012; Sunday et al., 2011].
- c. The implications of ocean acidification for the structure of ecosystems;
- d. The effect of multiple stressors [Byrne, 2011; Ericson et al., 2012; Wernberg et al., 2011], especially the combined impacts of likely environmental changes such as expansion of hypoxic zones and increased temperature [Brewer and Peltzer, 2009; Gruber, 2011] but also of shifting patterns of salinity e.g. [Durack et al., 2012].

Crucially there is a need to scale the understanding of ocean acidification impacts from “narrow” taxon-specific experiments to ecosystem-level experiments. Free Ocean Carbon Enrichment experiments or “FOCE” may provide important insights into ecosystem-level impacts of ocean acidification [Kline et al., 2012]. Ultimately there is a need to detect and reliably attribute ocean acidification impacts in nature. To date there are few in-situ studies that attempt to unravel the effects of ocean acidification (two in Australian waters [De’ath et al., 2009; Moy et al., 2009]) from other compounding factors and there is a need for ecosystem-level impact research [Russell et al., 2011a]. So far insights into ecosystem-level impact come from studies of naturally-acidified systems where CO<sub>2</sub> outgasses through volcanic vents [Fabricius et al., 2011; Hall-Spencer et al., 2008; Tunnicliffe et al., 2009].

## Policy implications and adaptation responses

### Key policy challenges

The previous sections have identified that:

- a. at its current level, ocean acidification may already be affecting some marine organisms (e.g. foraminifera) and ecosystems (GBR) and
- b. ocean acidification will continue to increase through and beyond the end of this century, thus having the *potential* to have much wider and long-lasting impacts on marine ecosystems.
- c. there remains, however, significant scientific uncertainty regarding the medium- and long-term degree and extent of possible impacts.

Governments are guided by legislation and policy frameworks that define their environmental, economic and social objectives (amongst others). On current evidence and scientific understanding of its observed and potential impacts, ocean acidification may pose a threat to the long term achievement of environmental objectives (an example, in the Australian context, is the Environmental Protection and Biodiversity Conservation Act). Through potential impacts on marine ecosystem services, ocean acidification may also pose risks to economic and social objectives (for example, those associated with maximising economic returns from fishing).

Policy makers are faced with the challenge of obtaining better information pertaining to the risks posed by ocean acidification, and of determining whether and how to develop mitigation and/or adaptation strategies.



### **Mitigation and adaption considerations**

Ocean acidification presents some unique policy as well as scientific challenges. Ocean acidification differs from global warming in that its impact derives from the chemistry of carbon dioxide (CO<sub>2</sub>) in seawater, rather than from its physical action as a greenhouse gas in the atmosphere. This means that increasing atmospheric CO<sub>2</sub> will inevitably increase ocean acidity, largely independent of the rate of global warming and its impacts, and independent of climate-model projections. Ocean acidification will need to be considered in the context of setting stabilisation targets for atmospheric CO<sub>2</sub> and the timelines on which the targets need to be reached. There are natural time lags involved in the marine carbon cycle, both in the uptake of CO<sub>2</sub> by the ocean as well as in the centuries needed to reverse the acidification already under way [Archer et al., 2009; Goodwin and Ridgwell, 2010]. These lags place a penalty on delaying limits on carbon emissions and a premium on early action. A further policy challenge arises because the only mitigation options available are reductions in carbon dioxide emissions or some form of carbon dioxide sequestration, or both. Ocean acidification would not be easily ameliorated by most proposed “geoengineering” strategies [Matthews et al., 2009], though some such strategies would specifically act by adding alkalinity and thus buffer the ocean [Kheshgi, 1995; Schuiling and Krijgsman, 2006]. The thresholds for atmospheric CO<sub>2</sub> levels at which acidification impacts begin may differ from those which trigger warming impacts, so mitigating acidification may require different emissions-limitation targets than mitigating global warming. Similarly, because acidification arises only from CO<sub>2</sub> emissions, limiting other greenhouse gases (such as nitrous oxide) will not mitigate ocean acidification.

## **Detailed Assessments of Key Oceanographic and Ecosystem Components, and Processes**

### ***Observations and Modelling***

The long-term secular changes in carbonate chemistry in the open ocean are now relatively well established [Doney et al., 2009; Doney, 2010]. A key challenge is characterising the progress of acidification in nearshore and shallow marine environments, such as coral lagoons and estuaries. These environments have high natural variability in carbonate chemistry and pH e.g. [Hofmann et al., 2011]. In some shallow-water environments, diurnal (through tidal and sun cycles) variability can exceed the mean decadal-scale change anticipated over the current century [Nguyen et al., 2012; Santos et al., 2011; Shaw et al., 2012], adding complexity to predictions of future carbon chemistry changes under ocean acidification. Bio-geochemical processes and their interaction with ocean acidification are only just starting to be identified and understood. Importantly, there are few baseline carbon chemistry measurements for these shallow environments. Physical changes, including warming, circulation patterns, intensity and frequency of storms, patterns of precipitation and sea level change, may all interact with ocean acidification.

Research is underway in Australia, New Zealand and overseas to improve the methods and equipment used for high-precision carbonate chemistry measurements. One initiative is the development of pH sensors that do not need constant calibration,

## Ocean acidification

which would enable improved consistency of measurements. These could also be used for remote deployment to deliver reliable, high-precision in-situ carbonate chemistry measurements. Another project is currently assessing the possibility of using commonly-measured oceanographic variables (e.g. depth, temperature, salinity and oxygen) to estimate alkalinity and dissolved inorganic carbon. This would enable translation of large-scale and long-term data sets (e.g. satellite estimates of sea-surface temperature) currently collected by the Australian Bureau of Meteorology into pH for large areas of ocean. Alkalinity and DIC will still need to be measured to assess changes in anthropogenic uptake of CO<sub>2</sub>.

Work is being undertaken to identify suitable proxies for carbonate chemistry from sediments, massive corals and coral reef limestone (palaeoceanographic records) that can be used to build a picture of marine carbonate chemistry prior to the Industrial Age. Understanding past changes through geological archives (e.g. deep-sea sediment cores and coral) will provide longer pH and ecological variability records than the historical observational record. In particular the past record of carbonate variability is the only source of documented changes in ocean carbon chemistry of comparable magnitude to those anticipated over the coming decades and centuries.

Monitoring of carbon chemistry in the open marine environment and some shallow coastal systems has already commenced in the Australasian region. The Integrated Marine Observing System (IMOS) delivers and integrates a range of data that contribute to research into ocean acidification<sup>1</sup>. Ships and moorings are used to measure CO<sub>2</sub> concentrations in surface ocean waters, and estimate fluxes of CO<sub>2</sub> between the atmosphere and ocean. Wavegliders are also showing potential for taking surface observations. There are currently three coastal carbonate chemistry moorings around the Australian continental shelf, and a time series station in the Southern Ocean. Bi-monthly measurements of marine carbonate chemistry have been made in the surface waters associated with the Subtropical Front of east New Zealand since 1998, and coastal pH is being measured in Wellington Harbour.

The viability of using oceanographic variables other than carbonate parameters themselves as proxies for carbon chemistry patterns and change shows promise for open ocean areas [McNeil et al., 2007; McNeil, 2010]. Spectrophotometric measuring systems, which do not require as much ongoing probe calibration as other systems, have potential for remote deployment in autonomous systems such as moorings and floats [Byrne and Yao, 2008; Martz et al., 2009; Seidel et al., 2008]. A particular observational challenge is represented by alkalinity, an often-utilised parameter for characterising the carbonate system and especially for inferring carbonate precipitation from seawater [Fransson et al., 2011; Ilyina et al., 2009]. The use of commonly-measured oceanographic variables (e.g. temperature, salinity and oxygen) to estimate alkalinity and dissolved inorganic carbon (DIC) in the open ocean may help complement in-situ direct measurements of the carbonate system, especially DIC and alkalinity e.g. [González-Dávila et al., 2010]. These approaches are so far limited in their applicability to shallow-water environments, where biological processes and

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<sup>1</sup> IMOS National Science and Implementation Plan

<http://imos.org.au/plans.html#c1210>; IMOS

Observations for Acidification Research, <http://imos.org.au/imosobsresearch.html>

## Ocean acidification

sediment-water interactions strongly influence seawater carbonate chemistry [Kleypas et al., 2011; Santos et al., 2011]

Proxies of carbonate chemistry from coral and sediment archives are proving useful to reconstruct past carbonate chemistry parameters in order to build a pre-industrial baseline of carbonate chemistry.

Modelling ocean acidification and its impacts faces the challenge of a wide range of spatial scales of variability, spanning from individual organisms to entire ecosystems and spatial scales ranging from local to global extent. Models are now focused on chemical and physical drivers of the carbonate system. Whereas physical transport and atmosphere-ocean fluxes of carbon are mainly well represented in models, pelagic and benthic biological processes and their role in modifying the ocean carbon chemistry are often highly simplified [Hood et al., 2006; Jin et al., 2006; Vichi et al., 2007]. At present, projections of the impacts of ocean acidification cannot be captured by a single model. Rather, hierarchies of models in which spatial, temporal and biological responses at the full range of spatial, ecological, and temporal scales can be separated and investigated are needed. Modelling socio-economic impacts is still in its infancy, however work is underway to extend the known organism-scale impacts of ocean acidification on molluscs to global economics and food security. This work has shown that the potential impacts of declining mollusc growth could be detrimental for some developing nations [Cooley and Doney, 2009; Cooley et al., 2009]. Such socio-ecological systems modelling is critical to help understand the impacts of ocean acidification on human societies now and in the future.

### Calcification processes

One implication of ocean acidification for Australian marine ecosystems is the impact acidification has on the process of calcification – the making of shells, plates and skeletons out of calcium carbonate ( $\text{CaCO}_3$ ) – for the variety of calcifiers important in Australian marine, and global ocean, communities such as corals, shelled plankton and others. Though calcification is only one of many biological processes likely to be affected by acidification, it is an important process in the formation of reef habitats and benthic substrates in a wide range of ecosystems, as well as a key process in the global carbon cycle. In a purely non-biological system, carbonate mineral formation would depend mainly on carbonate ion concentration, e.g. in household “hard water” calcium deposits. Biological calcification, however, is more complex than simple mineral precipitation, given the many biocalcifiers utilizing bicarbonate and metabolic  $\text{CO}_2$  e.g [Roleda et al., 2012] . Acidification affects the rate and energetic cost of calcification, as well as the dissolution of existing skeleton. Many experiments on calcifiers, whether they utilize bicarbonate or carbonate ion, show an apparent dependence of calcification on carbonate ion concentration. However many corals have the ability to up-regulate their internal pH during calcification e.g. [McCulloch et al., 2012a; Venn et al., 2011] and therefore exhibit a lower sensitivity than that predicted from decreases in seawater saturation state alone. The calcification response to increased bicarbonate ion is also complex and variable, and some organisms may be able to take advantage of increased bicarbonate availability to maintain or increase calcification e.g.[Jury et al., 2010; Marubini and Thake, 1999].

## Ocean acidification

The majority of research to date suggests that ocean acidification will reduce overall calcification in calcifying animals in both larval and adult life history stages [Byrne, 2010; Gattuso et al., 2011]. However many experiments suggest mixed impacts of ocean acidification on calcification processes for some organisms [Kroeker et al., 2010; McCulloch et al., 2012a; Miller et al., 2009; Pandolfi et al., 2003; Ries et al., 2009]. The calcifying algae coccolithophores in particular show mixed species and strain-specific responses to acidification [Iglesias-Rodriguez et al., 2008; Riebesell et al., 2000; Riebesell, 2004]. Some of the variable and species-specific responses however, are likely to be influenced by variable experimental approaches [Byrne, 2012; Schlegel et al., in press].

Calcification occurs with a variety of physiological mechanisms and in different tissues so generalisations are difficult [Turley et al., 2010]. Some taxa have unprotected external skeletons (e.g. abalone) directly exposed to changing ocean chemistry whereas others (eg. sea urchins) have internal skeletons protected by overlying tissue, a difference that influences vulnerability. [Byrne et al., 2011]. Many scleractinian corals appear to have the ability to up-regulate internal pH which effectively acts to raise their carbonate saturation state at the site of calcification [McCulloch et al., 2012a; Venn et al., 2011]. Species sensitivities and the potential mitigating effects on ocean acidification and energetic costs remain to be investigated. The potential of evolution and adaptation to a changing ocean (mainly in regard to temperature and CO<sub>2</sub>/pH) is also not well understood as few experiments have been carried out through multiple generations of organisms. Micro-organisms with short generation times (e.g. bacteria and phytoplankton such as coccolithophores) may be able to genetically adapt to a new environment [Collins and Bell, 2004; Lohbeck et al., 2012; Müller et al., 2010], however evolutionary timescales may vary among larger taxa as well.

Carbonate mineralogy affects the vulnerability of calcification and carbonate net accumulation to ocean acidification. Three calcium carbonate (CaCO<sub>3</sub>) polymorphs occur commonly in nature: aragonite, low-magnesium (Mg) calcite (LMC) and high-Mg calcite (HMC; >4mol% MgCO<sub>3</sub>) [Andersson et al., 2008]. Aragonite is more soluble than LMC [Mucci, 1983], and HMC with is in turn more soluble than calcite and aragonite [Morse et al., 2007]. Whereas aragonitic organisms are considered the most vulnerable to ocean acidification, high-Mg calcite organisms may be equally, if not more, susceptible. Physiologically, however, aragonite calcifiers may have pH-regulation mechanisms that may confer some resilience to acidification [McCulloch et al., 2012a]

A wide range of marine organisms produce skeletons/shells containing significant amounts of Mg, including echinoderms (2-12mol% Mg), benthic foraminifera (2-16%), coralline algae (7-20%), crustaceans (5-12%) [Chave, 1954]. Some Mg-calcite coralline algae can also form (Ca<sub>0.5</sub>Mg<sub>0.5</sub>CO<sub>3</sub>) and magnesite (MgCO<sub>3</sub>) [Nash et al., 2011] and it is not yet understood how rising CO<sub>2</sub> will affect these organisms.

Ocean acidification (OA) leads to reduced concentration of carbonate ions and in turn lowered carbonate mineral saturation states required to maintain shells. Thus OA poses a two-fold problem for species with calcium carbonate structures: (1) Exposed calcium carbonate structures such as shells may start to dissolve if saturation states fall low enough [Rodolfo-Metalpa et al., 2010] and (2) individuals would have to work harder to maintain their shells due to reduced carbonate concentrations in sea

water [Cummings et al., 2011], reducing energy available for other processes such as growth and reproduction.

In addition to impacts on calcification, increased levels of  $p\text{CO}_2$ , may affect essential physiological processes, such as metabolism and acid-base balance [Langenbuch and Pörtner, 2003; Munday et al., 2009b; Pörtner, 2008; Pörtner and Peck, 2010]. If experimentally-detected physiological responses to acidification occur in nature, they may result in a reduction of fitness for many species with repercussions on ecosystem function.  $\text{CO}_2$ -related physiochemistry and ocean warming may work synergistically [Pörtner, 2008].

### ***Corals***

Changes in coral reef ecosystems driven by acidification and other impacts, could affect societies that depend upon these ecosystems [Raven et al., 2005]. Calcification in corals throughout the Great Barrier Reef has declined by 14.2% since 1990 [De'ath et al., 2009] and projections of the saturation levels of the form of  $\text{CaCO}_3$  precipitated by corals – aragonite – suggest that calcification rates in many warm-water corals may decrease over the next century [Gattuso et al., 1998; Langdon and Atkinson, 2005]. However the joint effects of changing temperature [Cooper et al., 2012], and of internal pH-maintenance mechanisms [McCulloch et al., 2012a] complicate the projection of future acidification to coral growth. Similarly both coral and algal growth can alter seawater chemistry so as to mask or exacerbate the impacts of acidification [Anthony et al., 2011a]. Experiments suggest that ocean acidification will affect coral reefs by mid century, with risks arising both from reduced coral calcification rates in many taxa [Kleypas et al., 1999] and reductions in net community calcification [Silverman et al., 2009]. However, there is a great deal of variability in coral response to acidification and other impacts e.g. [Pandolfi et al., 2011], as well as physiological scope for resilience in calcification for many taxa [McCulloch et al., 2012a]. The impacts of warming-induced bleaching are also of concern [Anthony et al., 2011b]. These major stressors, warming and acidification, do not operate in isolation, with synergistic impacts observed in experiments [Anthony et al., 2008].

Cold-water corals may also experience difficult water chemistry conditions in the coming decades resulting in projected losses as high as 70% by 2100 [Orr et al., 2005] and some as early as 2020 [Guinotte et al., 2006]. Manipulative experiments show that reductions in pH significantly reduce cold-water coral calcification rates (30% and 56% respectively when pH drops by 0.15 and 0.3 units [Maier et al., 2009], however there is potential for acclimation to long-term shifts in carbonate chemistry [Form and Riebesell, 2012]

### ***Holopelagic Calcifiers: coccolithophores, foraminifera, shelled pteropods and other plankton***

Impacts on calcification in the planktonic  $\text{CaCO}_3$  producers – coccolithophores, foraminifera and shelled pteropods – are less well reported but of equal concern given these calcifiers account for nearly all of the export flux of  $\text{CaCO}_3$  from the upper ocean to the deep sea [Fabry, 2008; Schiebel, 2002].

## Ocean acidification

Coccolithophores – planktonic unicellular shelled algae – are considered to be the most productive calcifying organisms on Earth [Iglesias-Rodriguez et al., 2008; Riebesell et al., 2000] and the cosmopolitan species *Emiliania huxleyi* is one of the best-studied species in regard to ocean acidification. The process of photosynthetic carbon assimilation may be enhanced in coccolithophores under future ocean acidification [Iglesias-Rodriguez et al., 2008; Riebesell, 2004].  $\text{CaCO}_3$  production on the other hand, shows a diversity responses to increased  $\text{CO}_2$  in experiments [Lohbeck et al., 2012]. However, the majority of studies suggest a reduction in calcification in response to ocean acidification [Riebesell and Tortell, 2011], but this appears species- and even strain-specific. However, as with other marine organisms, the combined effects of multiple variables need to be considered [Lefebvre et al., 2011]. Coccolithophores are major contributors to marine primary production, and dominate the vertical supply of  $\text{CaCO}_3$  to the deep ocean, and are important components of open ocean and coastal marine ecosystems as well as the global ocean carbon cycle [Balch et al., 2011; Honjo et al., 2008; Iglesias-Rodriguez et al., 2002].

Foraminifera – unicellular shelled protists – are important calcifiers in planktonic and benthic ecosystems [Gooday and Jorissen, 2011; Schiebel, 2002]. Laboratory experiments suggest ocean acidification would reduce calcification in foraminifera, leading to lighter shells [Bijma et al., 2002; Lombard et al., 2010] and recently natural populations of planktonic foraminifera in the Southern Ocean have been found to have 30-35% lighter shells than their counterparts from pre-industrial times [Moy et al., 2009]. Similarly, recent-deposited planktonic foraminifera in Arabian Sea cores also show reduced calcification, also likely due to acidification [de Moel et al., 2009].

Pteropods – planktonic shelled gastropods – can reach densities of more than 10,000 individuals per cubic metre in high-latitude areas [Bathmann et al., 1991; Pane et al., 2004] and are important components of polar food webs, contributing to the diet of carnivorous zooplankton, North Pacific salmon, mackerel, herring, cod and baleen whales [LeBrasseur, 1966; Takeuchi, 1972]. Pteropods also contribute to carbonate fluxes in a range of marine environments [Accornero et al., 2003; Almogi-Labin et al., 1988; Bednarsek et al., 2012; Fabry and Deuser, 1992; Hong and Chen, 2002; Hunt et al., 2008; Jasper and Deuser, 1993; Meinecke and Wefer, 1990; Mohan et al., 2006; Pilskaln et al., 2004; Singh and Conan, 2008; Tsurumi et al., 2005]. Observations of pteropod populations in subantarctic waters since 1997 [Howard et al., 2011] suggest that their numbers and calcification may be declining in these waters [Roberts et al., 2011]. Similarly, observations of shell thickness and porosity in shelled pteropods in tropical Australian waters suggest a decadal reduction in calcification [Roger et al., 2012]. Impacts on calcification processes in these calcifiers is of particular cause for concern as pteropods make shells of aragonite, the more soluble form of  $\text{CaCO}_3$  than the calcite produced by coccolithophores and foraminifera, and polar waters in both hemispheres are likely to be especially at risk of aragonite undersaturation by the end of the century [McNeil, 2010; Orr et al., 2005; Steinacher et al., 2009]. Indeed, current laboratory experiments show reductions in pteropod calcification under higher  $\text{CO}_2$  [Comeau et al., 2009].

Similarly, experimental data on krill, a key component of the pelagic food web in the Southern Ocean, show impairment of embryonic development at  $\text{CO}_2$  levels likely to be seen by the end of this century [Kawaguchi et al., 2010].

***Benthic calcifiers: non-coral invertebrates (eg. benthic foraminifera, mollusks and echinoderms)***

In addition to corals a large suite of benthic species calcify and some of these such as molluscs and echinoderms are also major habitat providers and play key ecological functions. These groups also include species that calcify across both their planktonic and benthic life history stages. Larval shells are among the smallest and most fragile shells in the ocean, so the vulnerability of calcification in these life stage is of particular concern and is still poorly understood[Byrne, 2011]. Vulnerable early life history stages may be bottlenecks for species persistence[Byrne, 2010; 2011; Dupont et al., 2010].

***Benthic foraminifera***

Benthic foraminifera are important carbonate producers in many reef environments [Hallock, 2005]. Like their planktonic counterparts a number of benthic foraminiferal taxa show decreased calcification and faunal diversity under elevated CO<sub>2</sub> conditions [Dias et al., 2010; Dissard et al., 2010; Kuroyanagi et al., 2009; Uthicke and Fabricius, 2012]

***Molluscs and Echinoderms***

Molluscs and echinoderms play key roles in marine habitats by filtering and controlling habitat heterogeneity[Coen et al., 1999; Rodney and Paynter, 2006]. Echinoderms are keystone predators (e.g. sea stars) or grazers (e.g. urchins).

Molluscs and echinoderms are also a key source of food and deleterious effects on commercial species are of great concern. A recent review presents a model of marked production of shell fish in the future due to ocean acidification, at a time when increased human populations and food security will be a considerable challenge[Cooley et al., 2009].

Studies of bivalves and echinoids indicate that larvae reared under ocean acidification and hypercapnia are smaller and have less skeletal material, as well as evident abnormal development [Byrne, 2010; 2011; Dupont et al., 2010; Gazeau et al., 2010; Kurihara, 2008]. The stunting effect of ocean acidification may be caused by impaired calcification under lower mineral saturation conditions, hypercapnic developmental delay/depressed metabolism, teratogenic effects and energetic constraints in acid-base regulation, or a combination of these [Chan et al., 2011; Martin et al., 2011; Sheppard Brennand et al., 2010; Stumpp et al., 2011]. Adult bivalves also show reduced calcification under elevated pCO<sub>2</sub>[Gazeau et al., 2007]. Reduced larval size in a high pCO<sub>2</sub> ocean would have a negative impact on feeding and swimming ability and make larvae more vulnerable to predation[Allen, 2008; Przeslawski et al., 2008]. Depending on the species, and perhaps the developmental stage at which experimental incubations are initiated (eg. juveniles, adults[Byrne, 2012]) may also stunt growth of benthic life stages through reduced larval production and midstage growth e.g. [Barton et al., 2012]. Warming (up to a point) may ameliorate the negative effects of acidification on calcifiers by stimulating growth[Byrne, 2011; Sheppard Brennand et al., 2010; Walther et al., 2010]. However some calcifiers may not reach the calcifying larval stage in a warmer ocean[Brierley and Kingsford, 2009]. Non-calcifying

## Ocean acidification

echinoderm larvae appear to be more sensitive to warming than acidification [Nguyen et al., 2012].

### *Macroalgae*

Other important calcifiers include calcareous benthic algae (especially crustose coralline algae or “CCA”s) that precipitate either high-magnesium calcite or aragonite and perform the important function of ‘gluing’ the skeletons of corals together to create reefs. These organisms’ vulnerability to ocean acidification is still being studied but because they can secrete high-Mg calcite they are likely to be affected earlier than other groups of calcifiers [Anthony et al., 2008; Kuffner et al., 2007; McClintock et al., 2009; Nash et al., 2011], and so represent a key area of vulnerability in shelf ecosystems from the tropics to the Antarctic.

Experimental studies in the tropics and temperate localities [Russell et al., 2009] suggest high sensitivity of physiological and population-level processes of CCAs to ocean acidification. In particular, calcification, primary production and abundance are reduced, whereas skeletal dissolution and mortality increase with elevated pCO<sub>2</sub>. Interactions with other anthropogenic processes, such as warming and eutrophication, may exacerbate these responses of calcifying algae [Anthony et al., 2011b; Diaz-Pulido et al., 2012]. Natural experiments with elevated pCO<sub>2</sub> confirm experimental findings [Fabricius et al., 2011; Hall-Spencer et al., 2008]. Upright calcified macroalgae (e.g. *Halimeda*) are also important producers of sediment to reef environments; these calcifiers’ response to acidification also suggest reduced calcification under acidification [Sinutok et al., 2011]. Brown algae, which do not necessarily calcify, but are important carbonate producers in shallow marine ecosystems, also show reduced calcification under elevated pCO<sub>2</sub> near volcanic vents [Johnson et al., 2012]. Elevated pCO<sub>2</sub> may enhance the competitive ability of some seaweeds to overgrow corals, potentially tipping the balance in favour of non-calcified organisms [Diaz-Pulido et al., 2011].

Key knowledge gaps include: variability in responses across taxa and habitats, potential for adaptation to high CO<sub>2</sub>, identification of molecular, cellular and physiological mechanisms involved in the responses observed, and mineralogical responses.

### *Impacts on fish*

Despite the ecological importance of fishes in marine ecosystems, and their substantial socio-economic significance, relatively little research has been conducted into the effects of ocean acidification on fishes. One risk to fish is the acidosis (high pCO<sub>2</sub> in the bloodstream) induced under exposure to elevated environmental CO<sub>2</sub>, potentially causing acidosis which, at high levels may affect many cellular processes. Fish are generally considered to be more resistant to direct impacts of ocean acidification because they do not have extensive calcium carbonate skeletons. However they have a range of physiological vulnerabilities to elevated pCO<sub>2</sub> and associated changes in ocean chemistry. Impacts may include: reduced respiratory capacity and energetic costs of acid–base maintenance [Munday et al., 2009a; Munday et al., 2009c; Munday et al., 2011a]; impaired sensory performance and altered behaviour [Dixson et al., 2010; Munday et al., 2009b], especially in larval fish; effects



on otolith (earbone) calcification (though in some cases this formation appears to be unaffected or even enhanced [Checkley et al., 2009; Munday et al., 2011b]).

Most of the research in Australia on the impacts of ocean acidification on fish has focused on small coral-reef fishes that are amenable to experimental research, and focused on species that lay their eggs on the substratum (demersal spawners), including many commercially important species. Few studies have examined acidification impacts on species that release their eggs directly into the ocean (broadcast spawners). The latter may represent a critical knowledge gap - eggs and larvae of broadcast spawners may be more sensitive to elevated  $\text{CO}_2$  if they develop in the open ocean where  $\text{CO}_2$  is more stable than in shallow-water environments. Similarly, pelagic fishes may be more sensitive to elevated  $\text{CO}_2$  if they are similarly adapted to stable  $\text{CO}_2$  chemistry in the open ocean [Munday et al., 2008].

Previous studies show that the mortality of adult fishes is not directly affected by small increases in ambient  $\text{CO}_2$ . Similarly, fertilization and egg survival appears to be tolerant to high  $\text{CO}_2$ , at least in the species studied to date. Recent experimental results indicate that the growth and development of larval and juvenile reef fishes is also relatively unaffected by  $\text{CO}_2$  levels that might be experienced in the ocean by the end of this century [Munday et al., 2009c; Munday et al., 2011a]. Whether growth and development of species from other habitats, especially pelagic species, are similarly tolerant is unknown. Calcification of otoliths does not appear to be retarded by ocean acidification. Instead, otoliths are larger in larval fish exposed to high  $\text{CO}_2$ , possibly due to changed bicarbonate concentrations from acid-base compensation.

Fish exposed to high  $\text{CO}_2$  exhibit behavioural changes and sensory impairment that affects their capacity to detect appropriate habitats and avoid predators [Domenici et al., 2012; Ferrari et al., 2011; Munday et al., 2009b; Munday et al., 2010; Simpson et al., 2011]. Field experiments show that these behavioural changes could increase mortality rates of newly recruited fish and could lower population replenishment and affect patterns of population connectivity.

Elevated  $\text{CO}_2$  has been shown to reduce respiratory capacity in some reef fishes, but the ecological consequences are currently unknown, but one consequence could be reduced metabolic scope needed in a warmer ocean [Pörtner, 2008; 2010; Pörtner and Farrell, 2008]. In general, the metabolic performance of species and life stages with high oxygen demand, such as pelagic species and pelagic larvae, are predicted to be most sensitive to elevated oceanic  $\text{CO}_2$  levels.

### ***Microbial Processes***

The impact of shifts in carbonate chemistry on microbial communities and processes is still little understood e.g. [Bowler et al., 2009; Joint et al., 2011; Tortell et al., 1997; Witt et al., 2011]. However, a number of studies, including those carried out in NZ waters, have identified an increase in the activity of bacterial extracellular enzymes which indicates a potential increase in the breakdown of organic matter e.g. [Piontek et al., 2010]. Increasing seawater  $\text{pCO}_2$  also stimulates fixation of nitrogen ( $\text{N}_2$ ) by cyanobacteria in some experiments e.g. [Hutchins et al., 2009] though not in all cases [Law et al., 2012]. Possible reductions in nitrification under acidification may limit the the supply of nitrate by this microbial pathway [Hutchins et al., 2009].

## Ocean acidification

### *Paleoceanographic perspective and buffering by deep-sea and shelf carbonate sediments*

The injection of carbon to the ocean during the Paleocene-Eocene Thermal Maximum, with its associated acidification and carbonate dissolution, is often cited as an “analog” to the current acidification of the ocean [Hönisch et al., 2012; Leon-Rodriguez and Dickens, 2010; Ridgwell and Schmidt, 2010; Zachos et al., 2005]. The glacial-interglacial cycles of the Late Pleistocene also provide constraints on the response of marine ecosystems to repeated changes in carbonate chemistry of similar magnitude to anthropogenic acidification of the ocean to date [Hönisch and Hemming, 2005; Hönisch et al., 2009].

The response of calcite-dominated deep-sea sediments will depend on their eventual exposure to undersaturated water as fossil-fuel CO<sub>2</sub> penetrates the deep ocean. The depth to which the fossil-fuel carbon dioxide must be absorbed is a function of the calcite saturation horizon and its manifestation in carbonate dissolution. The CSH varies from 3100-2800 m in the basins of the SW Pacific [Bostock et al., 2011]. Evidence from sedimentary cores suggests calcite saturation has varied over glacial/interglacial cycles. In the Pacific Ocean CaCO<sub>3</sub> concentrations are greatest during the deglaciations and lowest during the transition from interglacial to glacial [Farrell and Prell, 1989; Hodell et al., 2001; Marchitto et al., 2005], whereas in the Atlantic and parts of the Southern Ocean carbonate concentrations are highest in interglacials [Crowley, 1983; Howard and Prell, 1994]. The processes responsible for this variability have been debated over the last 50 years and are focused around production versus preservation driven by both ocean circulation-driven partitioning and shelf-basin partitioning in carbonate deposition e.g. [Berger, 1970; Opdyke and Walker, 1992]. The underlying cause represents a fundamental link between ocean biogeochemistry and climate change. Models for the glacial ocean have suggested that increasing the global net dissolution rate of sedimentary CaCO<sub>3</sub> by 40% could reduce atmospheric CO<sub>2</sub> to glacial levels [Archer and Maier-Reimer, 1994]. The CaCO<sub>3</sub> content of deep sea sediments, however, is a complex interplay of changes in overlying carbonate production, dilution by terrestrial sediment/biogenic silica, transport by ocean currents, as well as dissolution from low [CO<sub>3</sub><sup>2-</sup>] deep waters, or corrosive pore waters, from organic matter degradation [Archer, 1996]. Several proxies have been used to assess changes in the carbonate ion concentration of the water column over time including shell weight, foraminiferal shell fragmentation and more recently the development of boron isotopes as proxies for pH and B/Ca ratios as proxies for carbonate ion concentration [Foster, 2008; Rae et al., 2011; Sanyal et al., 1995; Yu et al., 2007]. Reconstructions applying these proxies suggest the glacial ocean was 0.15 pH units higher than in interglacials [Hönisch and Hemming, 2005]. The current average surface ocean pH is ~0.1 units lower than at any time over the past 1 million years. Studies of the rates and distribution of the marine sedimentary response to past carbon cycle change will help inform our understanding of the future buffering of acidification.

The Australian continental shelf is composed of 80 to 100% carbonate in many areas, including unique ecosystems such as the Great Barrier Reef and extensive bryozoan and seagrass communities in the southern margin and in Torres Strait, respectively. The very high carbonate content reflects the contribution of calcifying organisms to ecosystem diversity and functioning. Calcification provides a key ecosystem service,

producing hard substrate for sessile organism attachment[Wood, 1995] and by generating reef-stabilizing cements[Manzello et al., 2008]. Calcification produces a range of carbonate mineralogies, with implications for the timing of dissolution-mediated buffering of ocean acidification, with high-Mg calcite being the earliest to dissolve from marine sediments[Andersson et al., 2008]. The diversity of calcification is still being studied[Smith et al., 2006; Smith and Girvan, 2010; Smith and Lawton, 2010], with many taxa showing a range of mineralogies. Recently, dolomite was observed in living coralline algae[Nash et al., 2011] and aragonite in hydrocorals in Antarctica[Riddle et al., 2008]. Though dolomite is stable in the marine environment it is, in principle, thermodynamically unlikely to form in these environments. A recent pilot study found high Mg-calcite to be the most abundant carbonate mineral in four northern Australian shelf regions with abundances between 35 and 50% (unpubl. data, R. Haese). As calcification of this mineral fraction is predicted to cease within this century due to ocean acidification, the implications for shelf habitats are profound[Andersson et al., 2007]. Sediment porewater chemistry also represents a still poorly-understood source of feedback processes to acidification especially the interaction with advection in permeable carbonate sediments [Santos et al., 2011] and high diurnal variability in reef environments[Shaw et al., 2012]. Extending the mapping of carbonate mineral distribution and predictions of future mineral stability to other continental shelf regions will assist in establishing a spatial context to changes in calcification and identifying the most threatened ecosystems.

### Research Priorities

While pH changes in the open ocean are relatively predictable and now well-documented, less is known about natural variations in the carbonate chemistry of shallow coastal systems and how these systems might respond to ocean acidification. The coast is dynamic so projections for the oceans can only partially guide what will happen to coastal regions, although an overall depression of pH levels from current baseline conditions seems likely e.g.[Christensen et al., 2011; McElroy et al., 2012]. We urgently need baseline observations of the carbonate chemistry of a range of shallow coastal systems with different sources and sinks of alkalinity. This fundamental information on the CO<sub>2</sub>-carbonate system of coastal systems is essential to inform ocean acidification experiments with marine organisms.

Ocean acidification has the potential to significantly affect calcification and a range of other processes in economically significant habitats (e.g., coral reefs, oyster beds), food webs, regionally important ecosystems (e.g. Southern Ocean pteropods) and with implications for planetary geochemical cycles (e.g. through corals, foraminifera, coccolithophores). However, our present understanding of the impact of ocean acidification on physiological processes is informed largely from short-term laboratory experiments whilst we currently know very little about the response of individual organisms, populations, and communities in natural settings and under gradual change scenarios[Doney et al., 2009]. Along with observations of carbonate chemistry. There is a need for baseline observations of important marine populations and wider community responses to acidification in key Australian marine ecosystems (e.g. Southern Ocean, Great Barrier Reef). In concert with this fundamental research, we need to understand how impacts on calcification and other processes will affect the overall structure and function of entire ecosystems and what the consequences of significant changes are

## Ocean acidification

likely to be in terms of those ecosystems especially important to the millions of Australians that depend on them for food, livelihoods, and tourism.

We also need to understand the potential for acclimatization (phenotypic plasticity) and evolutionary (genetic) adaptation of organisms to ocean change stressors especially for ecologically and economically important taxa. There are several major gaps in knowledge. A better understanding of the molecular and cellular mechanisms underlying the responses to will allow us to discern levels of perturbation. Determination of potential for evolutionary change will require targeted genetic e.g. [Sunday et al., 2011] and multigenerational studies e.g. [Lohbeck et al., 2012].

### Recommendations

Efforts need to focus on establishing a better understanding of the various calcification processes at different parts of the life cycle for key marine calcifiers and how these are expressed on community and ecosystem levels. We need more information on how non-calcifiers may respond to ocean acidification. The impacts of ocean warming and other impacts in multi-stressor studies are also important to consider.

Ecosystem approaches required include establishing baselines of current calcifiers population 'health', and monitoring in key areas (e.g. Southern Ocean, Great Barrier Reef, temperate systems such as the Great Australian Bight) as well as targeted laboratory process studies, manipulative experiments, community and ecosystem scale mesocosm and free ocean carbon dioxide enrichments (FOCE) experiments and ocean acidification model development on a range of temporal and spatial scales.

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## Ocean acidification

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