

Making it clear

A fresh look at the global problem of ocean acidification for those people who want to know a little more

In this guide we do four new things. We answer some key questions many people are now asking about ocean acidification. We say how sure the international scientific community is about what is already happening to the ocean, we discuss what the future may hold for the ocean in a high carbon dioxide (CO₂) world, and we explore the consequences for all of us of what is now happening.

Questions Answered follows on from the highly successful multilingual guide called *Ocean Acidification: The Facts*, which was launched in winter 2009 at the UN climate change conference at Copenhagen. *Questions Answered* is inevitably more technical in nature than *The Facts* as it begins to help champion the science and reasoning behind frequently asked questions.

By getting to the point and improving understanding around these critical issues, we hope that many more people will not only be better informed about ocean acidification, but will also act with greater consensus, greater ambition and greater urgency to tackle one of the most significant environmental issues faced by present and future generations.

Two years on from the Monaco Declaration

Two years ago I hosted a meeting of more than 150 leading marine scientists from 26 countries organised and supported by the Intergovernmental Oceanographic Commission, the Scientific Committee on Oceanic Research, the Government of Monaco and my Foundation. These scientists joined in a call for immediate action by policy makers to reduce carbon dioxide emissions. A sharp reduction was urged from that meeting to avoid widespread and severe damage to marine ecosystems from ocean acidification. This warning formed the heart of the Monaco Declaration to which I was happy to lend my full support.

Two years on, significant work has been undertaken by science teams around the world on ocean acidification. Sometimes the results from this work confounded early predictions on the impacts of ocean acidification, but most of what we have learnt since the Monaco Declaration substantially increases concern about the speed and potential scale of impact that our emissions of carbon dioxide will have on the ocean, and in turn on us.

I am delighted that my Foundation supports *Ocean Acidification: Questions Answered*. Once again the science world has come together, this time in concert with the Ocean Acidification Reference User Group, to tackle a new issue – that of uncertainty and misinformation about ocean acidification.

I am convinced that armed with these clarifications and answers to new questions that have arisen, this work will help unlock decisions and overcome barriers that stand in the way between us and more rapid progress to tackle ocean acidification.

HSH Prince Albert II of Monaco



Photo © Palais Princier

Setting the scene

Since the end of the first Industrial Revolution in the 1830s widespread burning of fossil fuels, deforestation and cement production has released more than 440 billion metric tons of CO₂ into the atmosphere (half of it in the last 30 years). This mass release of previously 'locked away' carbon enhances the natural greenhouse effect, and jeopardises the future stability of the Earth's climate. Fortunately for us more than half of this extra CO₂ has been taken up by vegetation and the ocean, greatly slowing the rate and extent of impacts of climate change observed to date, but with other consequences, especially for the ocean.

The 'other CO₂ problem'

When the additional CO₂ released into the atmosphere dissolves in sea water, several chemical changes occur. These are collectively known as ocean acidification – also as the 'other CO₂ problem' and 'the evil twin of climate change'. Ocean acidification has only recently been noticed, yet its implications may be as great as the global temperature increases arising from climate change. Indeed, whilst climate change may be diffuse and difficult to track, ocean acidification is measurable, predictable and progressive. Recent studies show that the current uptake of CO₂ by the surface waters of the ocean – and the resulting rate of ocean acidification – is about 100 times quicker than at the end of the last glacial (20,000 yrs ago), the last time CO₂ significantly rose.

View of cold water coral reef at 220m water depth taken from the research submersible JAGO.

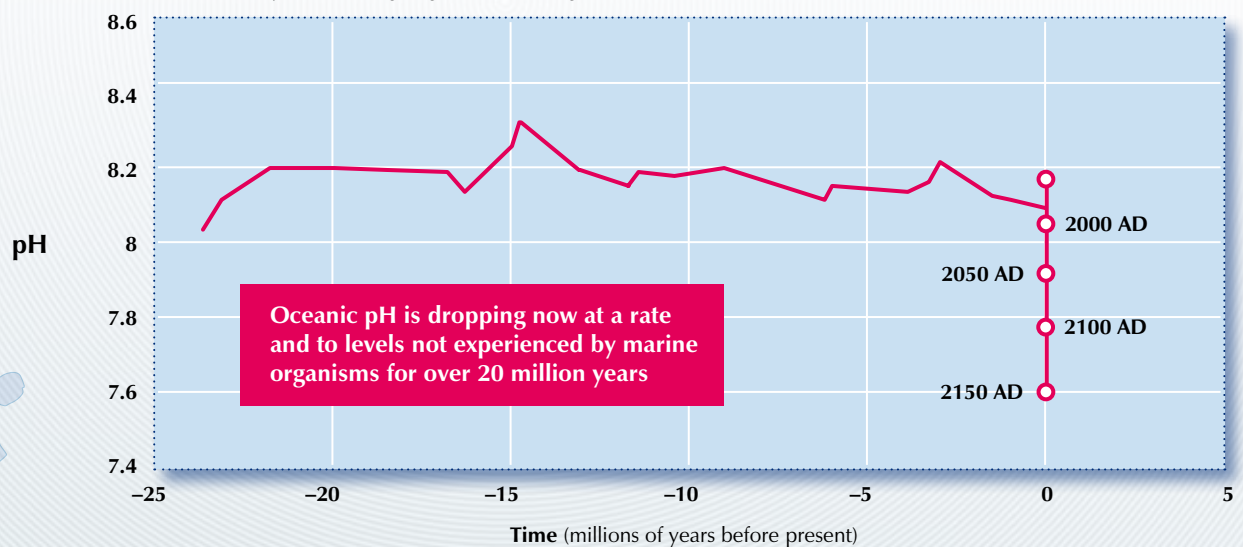


Photo © Karen Hasemann, IFM-GEOMAR

Oceans are acidifying fast

Changes in oceanic pH over the last 25 million years

Source after Turley et al. in *Avoiding Dangerous Climate Change* (2006).



Resolving confusion, providing clarity

Ocean acidification first emerged as a high profile issue beyond the scientific community in 2005 with the publication of the Royal Society report. It had previously been reported in the literature as far back as the 1970s but more consistently some ten years before the Royal Society report. Since 2005 major scientific studies have started around the world and although there are many unanswered questions there is considerable scientific consensus that ocean acidification is both real and is a major threat to our way of life. The Inter-Academy Panel on International Issues Statement on Ocean Acidification for example states that 'Even with stabilisation of atmospheric CO₂ at 450ppmv¹, ocean acidification will have profound impacts on many marine systems. Large and rapid reductions of global CO₂ emissions are needed globally by at least 50% by 2050.'

One of the challenges in getting the message out on ocean acidification is that many people find the science complex and confusing – issues which now have to be resolved, and quickly. This is vital if we are to act with the collective ambition and urgency needed to dramatically reduce our CO₂ emissions, and lessen over time the changes now being seen in the ocean from acidification. To help this process, in the winter of 2009 and directly after the UN climate change conference in Copenhagen, 27 leading scientists from 19 institutions and five countries came together to provide information and answers to many of the common questions that are now being asked about ocean acidification.² This scientific analysis and discussion forms the basis for this new guide.

The waters of the Antarctic are one of the areas where changes in ocean pH are happening fastest.

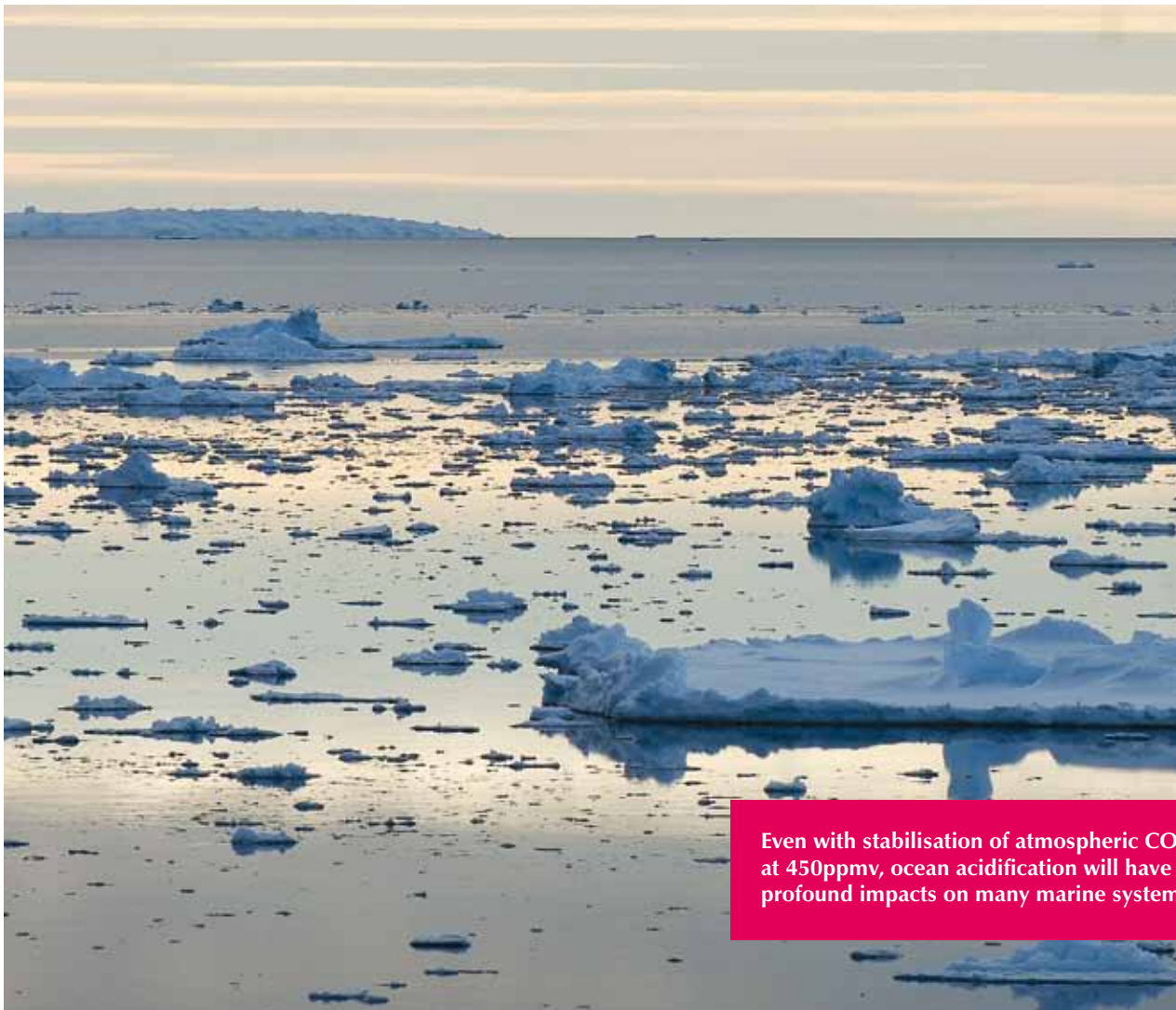


Photo © John M. Baxter

Even with stabilisation of atmospheric CO₂ at 450ppmv, ocean acidification will have profound impacts on many marine systems.

1. ppmv is parts per million by volume (one part per million by volume is equal to a volume of a given gas mixed in a million volumes of air).

2. This is the work of the U.S. Ocean Carbon and Biogeochemistry (OCB; www.us-ocb.org) program, supported by the European Project on Ocean Acidification (EPOCA; <http://www.epoca-project.eu/>) and the UK Ocean Acidification Research Programme (<http://www.oceanacidification.org.uk>). Leading ocean acidification scientists compiled responses to a list of 39 frequently asked questions (FAQs) that were subject to open peer review.

Major studies underway or in advanced stages of planning

EUROPEAN UNION

The European Commission has funded the European Project on Ocean Acidification (EPOCA), an initiative to investigate 'ocean acidification and its consequences' as a multinational effort that includes 31 partner institutions located in ten European countries. EPOCA research, already underway, aims to monitor ocean acidification and its effects on marine organisms and ecosystems, to identify the risks of continued acidification, and to understand how these changes will affect the Earth system as a whole. A new project 'Mediterranean Sea Acidification under changing climate' (MedSeA) will specifically target ocean acidification in the Mediterranean and will start shortly.

GERMANY

Biological Impacts of Ocean Acidification (BIOACID). This coordinated project involving 18 research institutions is funded by the Federal Ministry of Education and Research (BMBF) for an initial 3-year period starting in September 2009. Its main focus is on the effects of ocean acidification on the marine biota at the sub-cellular to ecosystem levels and their potential impacts on ecosystem services and biogeochemical feedbacks.

CHINA

Ministry of Science and Technology (MOST) and National Science Foundation of China (NSFC) have started to support research on ocean acidification. CHOICE-C is a newly funded 5-year project to study high CO₂ and ocean acidification issues in Chinese marginal seas, a joint project of seven major institutions with funding of 34 million RMB. NSFC started to fund projects on ocean acidification in 2006, and there are several ongoing national-level projects exploring the impacts of ocean acidification on calcifying organisms.

REPUBLIC of KOREA (South Korea)

The Korea Science and Engineering Foundation is funding the 5-year Korea Mesocosm Project to examine the effects of elevated CO₂ and temperature on natural phytoplankton assemblages, which involves five Korean laboratories.

JAPAN

Five major programmes in Japan fund research relevant to ocean acidification. Japan's Ministry of Environment supports research programmes to elucidate the future impact of ocean acidification on various marine organisms using sophisticated mesocosm facilities (e.g. AICAL, Acidification Impact on CALcifiers). MEXT (Ministry of Education, Science, Sport and Culture) and JAMSTEC (Japan Agency for Marine Science and TEchnology) also support ocean acidification research such as modelling efforts on the Earth Simulator supercomputer to predict future ocean conditions.

UNITED KINGDOM

In 2004 – 2007 a study was undertaken on the Implication for the Marine Environment of CO₂ (IMCO₂), funded by the Government departments of Defra and DTI. In spring 2009 the UK announced a 5-year £12 million programme to investigate changes in ocean ecosystems in response to ocean acidification (costs shared by the Natural Environment Research Council and Department for Environment, Food and Rural Affairs (Defra) and the Department of Energy and Climate Change (DECC)). The programme involves 21 research institutions across the UK and this programme collaborates with EPOCA and BIOACID.

UNITED STATES

The Federal Ocean Acidification Research and Monitoring Act: of 2009. The FOARAM Act in U.S. Public Law 111-11 was signed by President Obama in March 2009. In accordance with the Act, the National Oceanic and Atmospheric Administration, the National Science Foundation, and other federal agencies are working together with the Ocean Research and Resources Advisory Panel (ORRAP) Task Force on Ocean Acidification to develop a national programme on ocean acidification. Starting this year, the Interagency Working Group on Ocean Acidification has been gathering these groups' inputs and assembling a national plan for ocean acidification monitoring, research, assessment of implications, and strategies for conservation that will be submitted to Congress in March 2011. Several of the agencies have already begun to fund some of the ocean acidification research, monitoring and outreach activities outlined in the FOARAM Act.

AUSTRALIA

Ocean acidification in Australia focuses on the Antarctic and Australasian regions. The Antarctic Climate & Ecosystems Cooperative Research Centre (a partnership of AAD, University of Tasmania, CSIRO, DCCEE, NIWA (New Zealand) and AWI (Germany)) is sponsoring research in the Southern Ocean that includes monitoring sea water chemistry changes and the responses of key species. In the tropics, a collaborative observational and modelling programme between CSIRO, NOAA (USA), NIES (Japan) and University of Queensland has begun in the Great Barrier Reef and South Pacific regions. The vulnerability of the Great Barrier Reef to ocean acidification is also being addressed by the Australian Institute of Marine Science and several universities (Australian National University, University of Queensland, University of Sydney, James Cook University), through large-scale monitoring of reef waters, palaeontological reconstructions from coral cores, and field and laboratory experiments on reef organisms.

Getting the facts straight

For many who encounter ocean acidification for the first time two key questions arise – what is it, and is it real?

Such a reaction is shaped by a genuine lack of familiarity about the ocean; confusing perspectives about whether climate change is real; and surprise that there is another big issue ‘out there’ alongside climate change that we are only just hearing about.

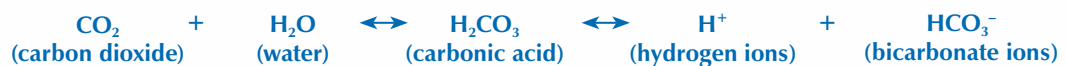
Most people react with the view that whatever ocean acidification is it can't be any less or more real than climate change, and can't really be anything very different. So they couple it to climate change and the changing fortunes of that issue as reported in the press. People can only cope with a finite list of issues to worry about and as this appears distant to them they simply move on with their day-to-day lives. They remain largely unaware that whilst the uncertainty around some aspects of climate change may be difficult to quantify, there is much less uncertainty around the basic concepts of what ocean acidification is and whether it is happening.

What is ocean acidification?

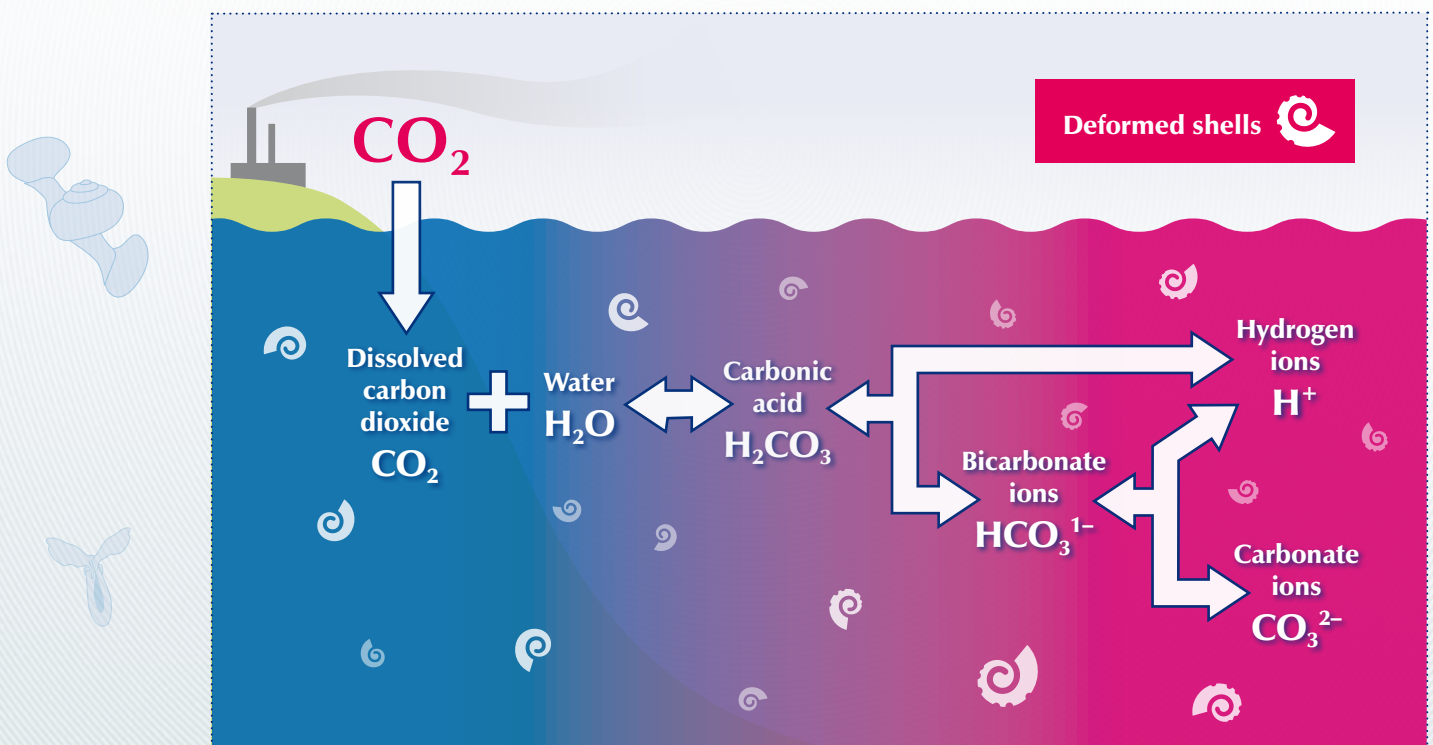
The shift in the ocean towards more acidic (or less basic) conditions is happening because of the ever-increasing amount of CO_2 in the atmosphere. This is known as ocean acidification. It occurs when CO_2 reacts with sea water to produce an acid. The faster the increase of CO_2 in the atmosphere, the faster the acidification of the ocean.

Understanding ‘carbonate’ and ‘acidity’

Ocean acidification is very different from climate change. Climate change represents a much larger set of consequences of human activity affecting a range of processes in ways whose frequency, scale and effects range from predictable to highly uncertain. Ocean acidification is the effect of CO_2 on the ocean as it is absorbed by the sea water. The term ‘ocean acidification’ summarises several processes that occur when CO_2 reacts with sea water. Two reactions are particularly important. Firstly, the formation of carbonic acid with subsequent release of hydrogen ions:

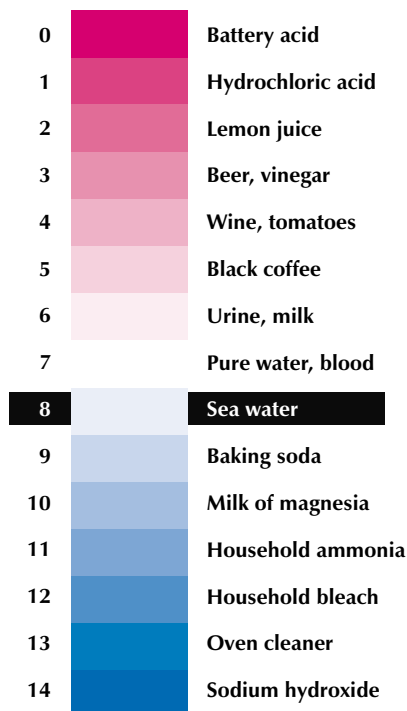


The burning of fossil fuels result in increased CO_2 in the atmosphere being taken up by the ocean resulting in it becoming more acidic. Source University of Maryland.

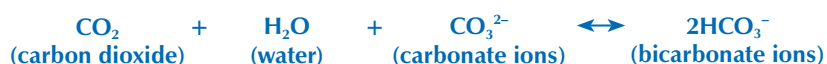


The pH scale

The pH scale is a measure of how acidic or basic (alkaline) a solution is. It was devised in 1909 and is a logarithmic index for the hydrogen ion concentration in an aqueous solution. The scale is the 'wrong way round', in that pH values decrease as hydrogen ion levels increase. Pure water has a pH of 7; lower values are considered acidic; higher values, basic. A solution of pH 4 is ten times more acidic than one of pH 5, and a hundred times more acidic than one of pH 6. Sea water currently has a pH of around 8.1, and is therefore considered a weak base. Whilst the pH range is usually given as 0 to 14, lower and higher values are theoretically possible.



The above reaction and release of hydrogen ions increases acidity thus reducing pH (see box above). A second reaction, between carbonate ions, CO₂ and water producing bicarbonate ions also occurs:



The combined effect of both these reactions is not only to increase acidity but also to lower the availability of carbonate ions. Carbonate ions are needed for calcification, the process describing the production of calcareous shells and skeletons. Such a reduction in carbonate ions has great biological significance, since it can affect the rate at which marine organisms – such as corals, molluscs, crustaceans, sea urchins and some algae – build their calcareous shells or skeletons. Under low pH conditions (higher acidity), carbonate ions are less available and calcification is therefore harder to achieve, and may be prevented altogether. This impact of ocean acidification may therefore have potentially catastrophic consequences for ocean life and many species of economic importance.

The concept of 'acidification'

The ocean currently has a pH greater than 7.0 and is therefore 'basic'; it is nearly impossible, chemically, for all of it to actually become 'acidic'. Why do we therefore refer to 'ocean acidification'? That is because acidification is the direction of travel, the trend, regardless of the starting point. The same term is used elsewhere, for example in wine making, blood chemistry and soil science, to refer to increasing acidity, regardless of whether the initial conditions are acidic or basic. A direct comparison can be made to the words we use to describe temperature changes: an increase from 0°C to 5°C is still cold (for most of us), yet is called 'warming'.

Various factors can locally influence the main chemical reactions of CO₂ with sea water and add to the effects of ocean acidification. For example, acid rain, which consists of sulphuric and nitric

Experiment investigating the effect of ocean acidification and elevated temperatures on coralline algae.



Photo ©Sophie Martin (CNRS)

acids originally derived from fossil fuel combustion, falls on the coastal ocean. Acid rain can have a pH between 1 and 6; its impact on surface ocean chemistry may be important locally and regionally but is very small globally. Coastal waters are also affected by excess nutrient inputs, mostly nitrogen, from agriculture, fertilizers and sewage. The resulting eutrophication leads to large plankton blooms, and when these blooms collapse and sink to the sea bed the subsequent respiration of bacteria decomposing the algae leads to a decrease in sea water oxygen and an increase in CO₂ (a decline in pH).

How sure are we that ocean acidification is really happening?

A very high degree of certainty

There is very high certainty that sea water chemistry is changing due to rising atmospheric CO₂, and that human activities are the root cause.

The strongest evidence is provided by detailed measurements in many parts of the world; for example, the 20-year record from the Pacific (off Hawaii) as shown below. Although there is high seasonal variability, there is an unambiguous trend for increasing dissolved CO₂ in the upper ocean, whilst pH is falling. These trends closely match the changes in atmospheric CO₂. Because the pH scale is logarithmic, the observed, apparently small pH drop of about 0.1 units since the pre-industrial era actually already represents a 30% increase in the abundance of hydrogen ions.

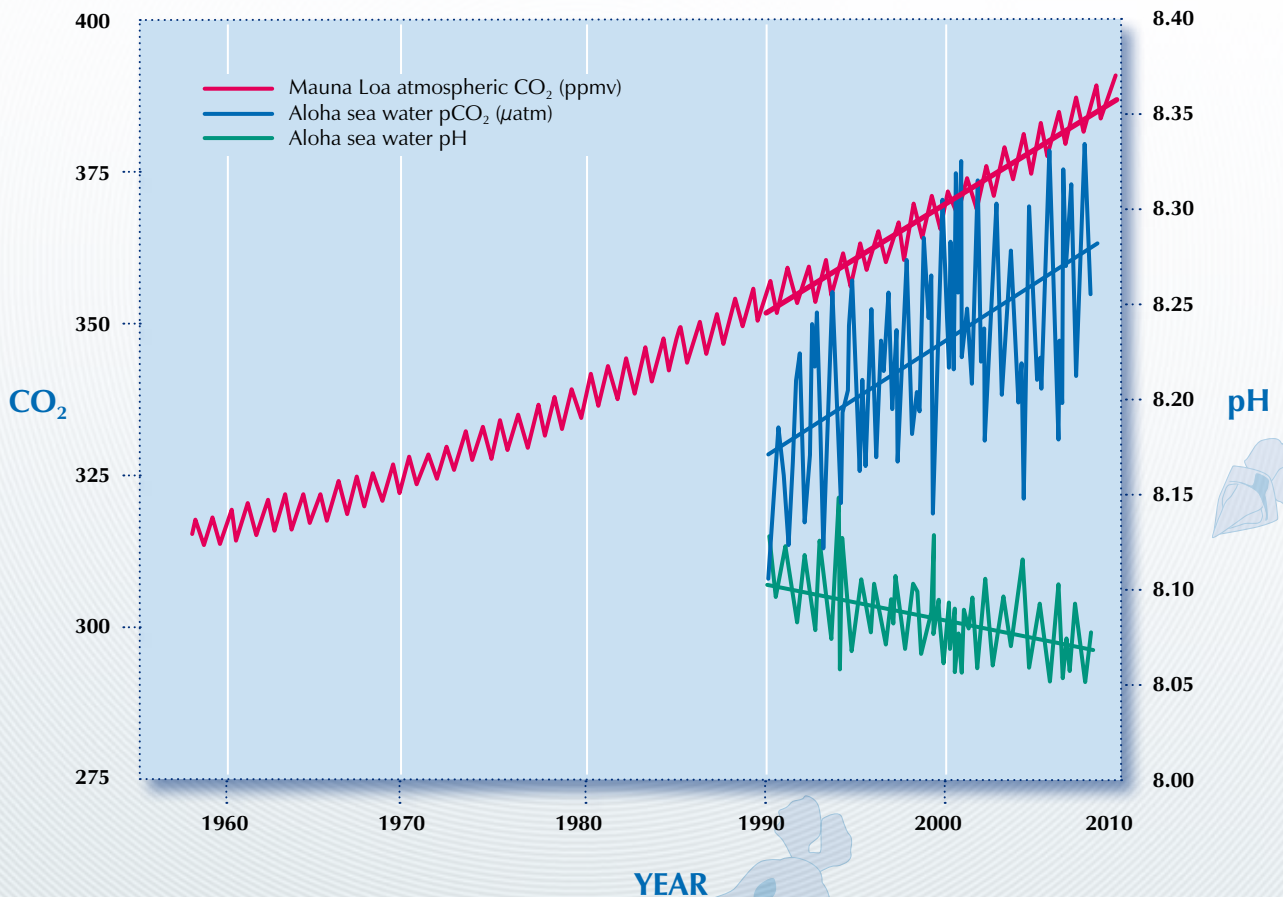
Computer models that explicitly include the recent, anthropogenic CO₂ releases closely simulate the observed decreases in sea water pH and carbonate levels. There is no other cause that can possibly be responsible for the worldwide effects that are observed.



Photo © Christopher Sabine

A NOAA mooring in the Pacific used to measure CO₂ fluxes.

Time series records of atmospheric CO₂ at Mauna Loa and surface pH and pCO₂ at Pacific Ocean station Aloha. Source after Feely *et al.*, *Oceanography* (2009).



Different oceans, different rates

Whilst ocean acidification will occur everywhere, it will happen more rapidly in some parts of the world than others, and impacts will also vary, because of differences in temperature and circulation patterns. Carbonate levels in sea water which are presently high enough to allow calcium carbonate structures like shells and skeletons to stay intact ('oversaturated' conditions), can drop to levels that will mean these hard structures will begin to dissolve ('undersaturated' conditions). Model-based predictions show that the Arctic Ocean will be first to cross this ocean acidification-related chemical threshold, when waters change from 'oversaturated' with calcium carbonate to 'undersaturated'.

If levels of atmospheric (and oceanic) CO₂ continue to rise at current rates, then by 2018 around 10% of the Arctic Ocean is projected to have crossed this threshold, rising to one-half of the Arctic Ocean by 2050. By 2100 it is likely that the entire Arctic Ocean will be in a state that can dissolve unprotected calcium carbonate structures.

There is a very high certainty that sea water chemistry is changing due to rising atmospheric CO₂, and that human activities are the root cause.



Photo © Ulf Riebesell, IFM-GEOMAR

EPOCA project staff working on a mesocosm enclosure during a CO₂ perturbation experiment in the high Arctic off Svalbard.



Photo © Jean-Pierre Gattuso

Mesocosm experiments are vital to help understand the implications of ocean acidification at the community and ecosystem levels.

National Center for Atmospheric Research Community Climate System Model 3.1 (CCSM3) modelled decadal mean pH at the sea surface for 1875, 1995, 2050 and 2095.

Source after Feely *et al.*, *Oceanography* (2009).

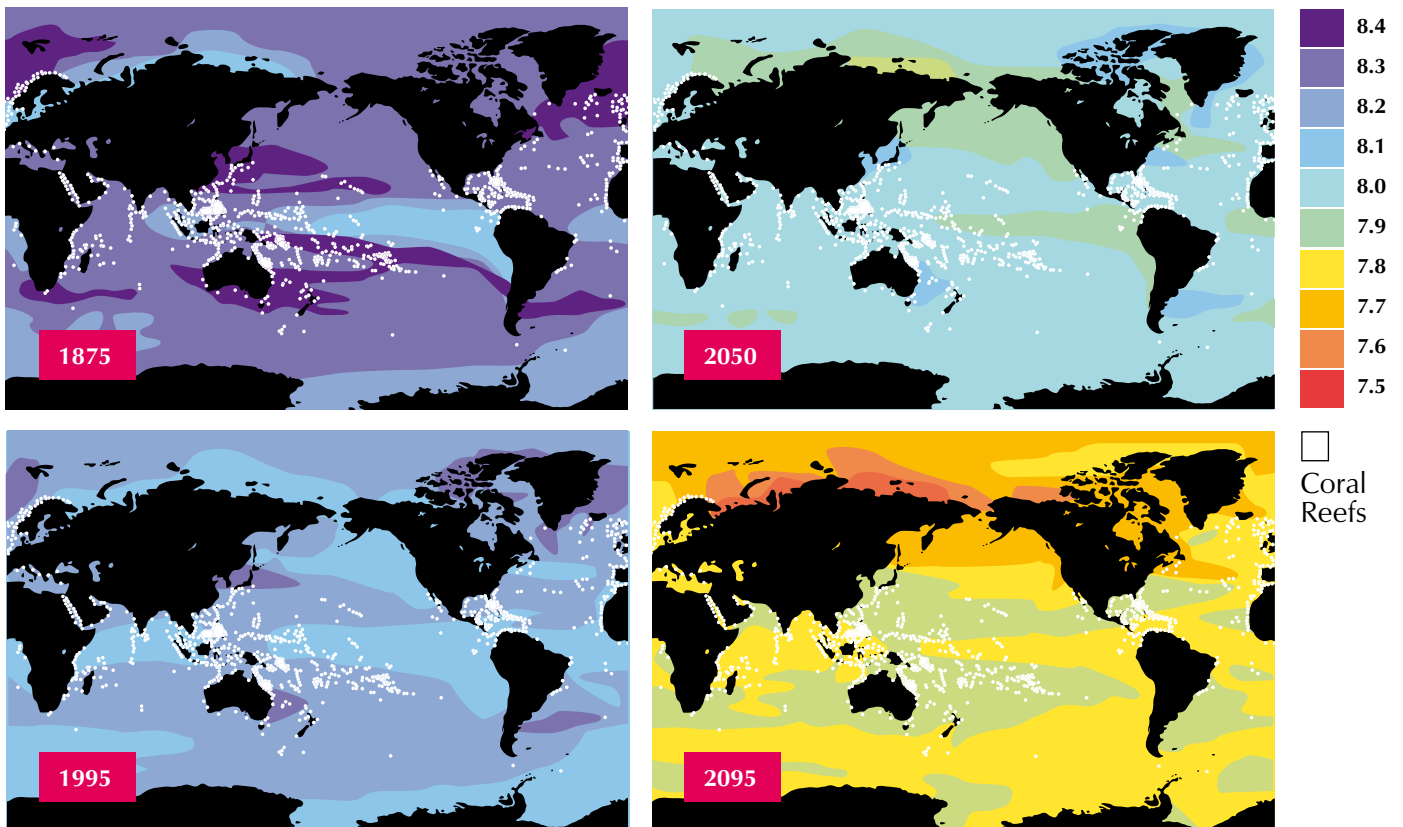


Photo © MNCRS/NH



The common sea urchin *Echinus esculentus* has a test made of calcite.

Calcite and aragonite

Calcite and aragonite are two different forms of calcium carbonate. Calcite is the mineral form found in the shells of coccolithophores (planktonic algae), foraminifera (amoeboid protists), some corals, echinoderms, and some molluscs (e.g. oysters); it is relatively less soluble.

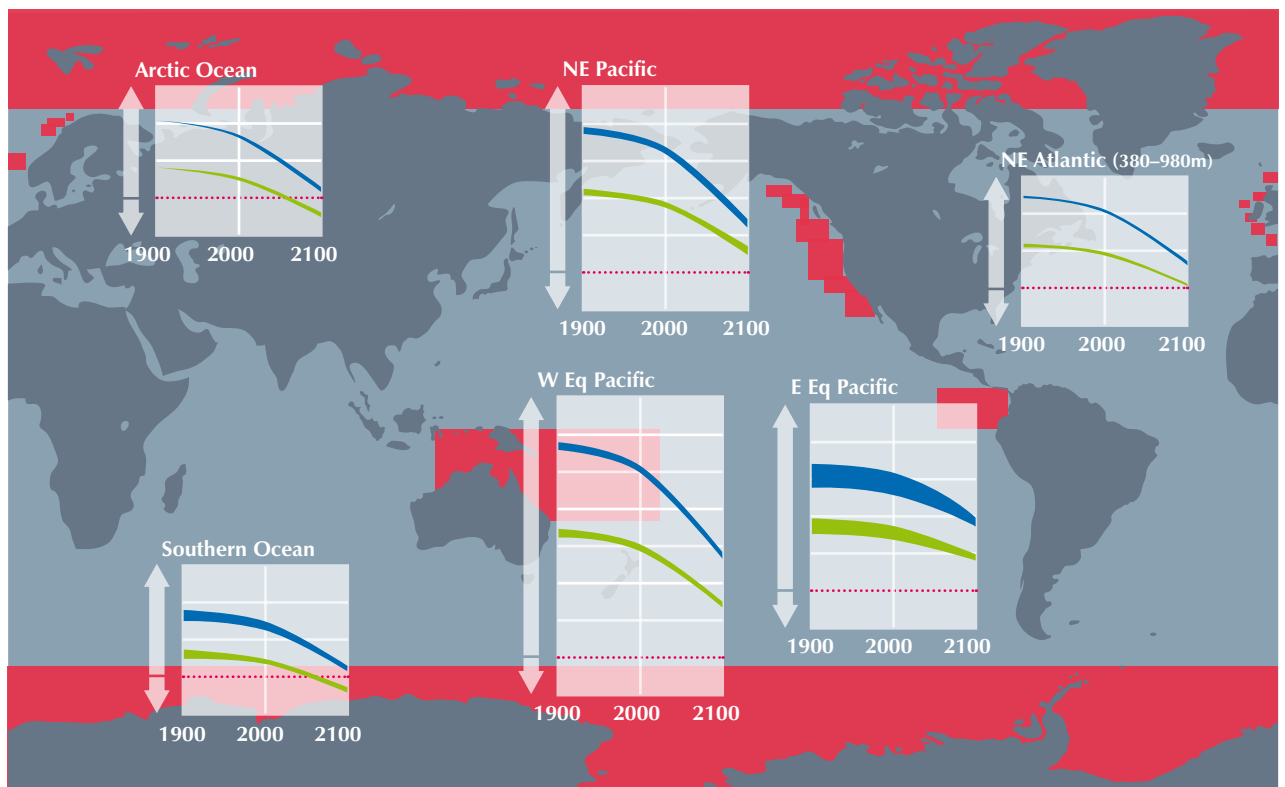
Aragonite is a more soluble form of calcium carbonate; it is found in most corals, most molluscs (including free-swimming pteropods (small planktonic snails)), as well as some species of algae.



The pteropod *Cuvierina columnella* has an aragonite shell.

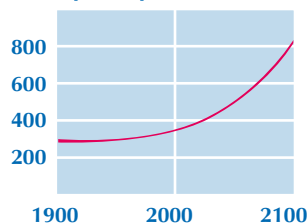
Photo © Hapcor/UAFCOML

Estimated historical, plus projected future changes in ocean chemistry assuming a business-as-usual CO₂ emissions scenario. Map plots show carbonate saturation state for six illustrative regions (shaded red) – values above the red horizontal dotted line represent oversaturated conditions, and below, undersaturated conditions for both calcite and aragonite. The thickness of the saturation lines indicates the seasonal range. Global ocean surface averages of atmospheric pCO₂, pH, and calcite and aragonite saturation, are shown bottom right. Source after Turley et al., *Marine Pollution Bulletin* (2010).

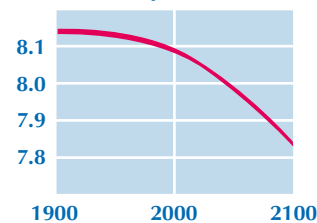


— Calcite
— Aragonite

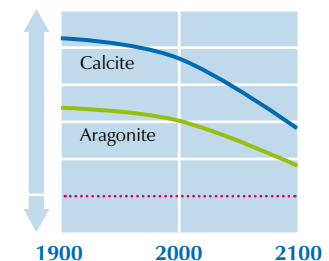
Atmospheric pCO₂ (µatm)



Surface ocean pH (SWS)



Surface saturation



Saturation horizons

Deep, cold ocean waters are naturally undersaturated with carbonate ions causing the shells of most calcifying organisms to dissolve. Surface waters are oversaturated with carbonate ions and do not readily dissolve shells. The saturation horizon is the level below which calcium carbonate minerals undergo dissolution. Those organisms that can survive below the saturation horizon do so due to special mechanisms to protect their calcium carbonate from dissolving. As ocean acidification causes this horizon to rise vertically in the water column so more and more calcifying organisms will be exposed to undersaturated water and thus vulnerable to dissolution of their shells and skeletons. The saturation horizon of calcite occurs at a greater ocean depth than that for aragonite, but both horizons have moved closer to the surface by between 50 and 200m compared to the 1800s.



Scleractinian corals such as *Lophelia pertusa* (white coral) build their skeletons out of aragonite and are especially vulnerable to a rising saturation horizon. Gorgonian corals (red coral) build their skeletons of calcite.

Photo © Karen Hismann, IFM-CEOMAR

Ocean acidification and the short and long-term fate of carbon in the system

On long timescales (>100,000 years) there is a natural balance maintained between the take-up and release of CO₂ on Earth; the CO₂ produced by volcanoes, the main natural source of CO₂, is taken up by the production of organic matter by plants and by rock weathering on land. However, rock weathering takes tens of thousands of years so will not remove the current anthropogenic input of CO₂ to the atmosphere and ocean fast enough. On shorter time scales (>1,000 years), the ocean has an internal stabilising feedback linking the ocean carbon cycle to the underlying carbonate rich sediment known as carbonate compensation.

The upper layers of the ocean tend to be supersaturated with CaCO₃ so little dissolution takes place, whilst the deep ocean is undersaturated and carbonate readily dissolves. The first boundary between these two states is known as the lysocline, the depth at which dissolution strongly increases in the deep ocean. The CaCO₃ in the form of dead shells sink to the sea bed; at shallow water depth the majority is buried in the sediment and trapped for a long time, but where the



Seabed sediments can act as a sink for calcium carbonate.

shells sink in deep water nearly all the CaCO₃ is dissolved, thereby not locking the carbon away for millions of years.

The current increased rate of dissolution of atmospheric CO₂ into the ocean is resulting in an imbalance in the carbonate compensation depth (CCD), the depth at which all carbonate is dissolved. As the pH of the ocean falls this results in a shallowing of the lysocline and the CCD, thus exposing more of the shells trapped in the sediments to under-saturated conditions causing them to dissolve, which will help buffer ocean acidification but over a long time scale of a thousand years.

Photo © Deep Atlantic Stepping Stones Science Team IFE UR/N/O/A

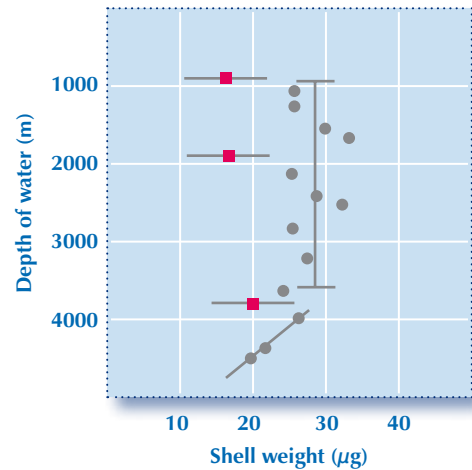


The planktonic foraminifer *Globigerina bulloides* recovered from a sub-Antarctic water column sediment trap has a shell made of calcite.



Photo © Andrew Moy

weight loss in the shells of foraminifera such as *Globigerina bulloides*, and other planktonic species in polar waters, such as pteropods, whose shells are made from the more soluble aragonite form of calcium carbonate is a cause of concern. Pteropods play important roles in Antarctic food webs, feeding many organisms, including fish; they help create a long term storage of atmospheric carbon to the deep ocean on their death through their shells acting as a ballast to carry organic carbon of the dead animals to the ocean floor.



Higher latitudes, lighter plankton?

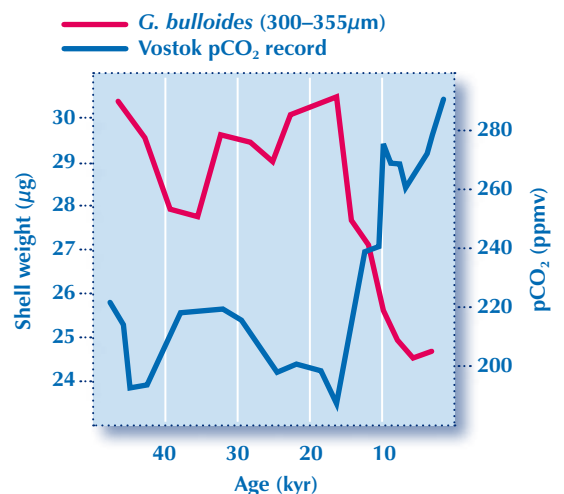
Aragonite undersaturation (i.e. the chemical state where dissolution starts) is predicted to start occurring in Southern Ocean waters between 2030–2070. Laboratory experiments and direct observations suggest that the decreasing carbonate levels occurring well before then will make it increasingly difficult for many organisms to make and/or maintain their shells. Samples from the Southern Ocean suggest that the shells of present-day planktonic foraminifera are already 30-35% lighter than their pre-industrial counterparts. With CO₂ emissions continuing to increase, the observed

Average shell weights of *Globigerina bulloides* (300 – 355 µm) collected from various depths above the calcite saturation horizon (red squares) are lighter compared with those collected from pre-industrial era sediment cores (grey circles). Source after Moy *et al.*, *Nature Geoscience* (2009).

A living *Limacina helicina antarctica* pteropod collected aboard the Research Vessel Umitaka Maru during the 2008 International Polar Year (IPY) Collaborative East Antarctic Marine Census (CEAMARC) expedition.



Photo © Hopcroft/ UAF/COML



Shell weights of *Globigerina bulloides* were highest when atmospheric CO₂ levels were lowest (around 18,000 years ago), and are lowest now when atmospheric CO₂ levels are at their highest. Source after Moy *et al.*, *Nature Geoscience* (2009).

West coast of America where upwelling of deeper undersaturated waters is already having an impact.



Photo © Dan Lufkley

Ocean problems coming to the surface

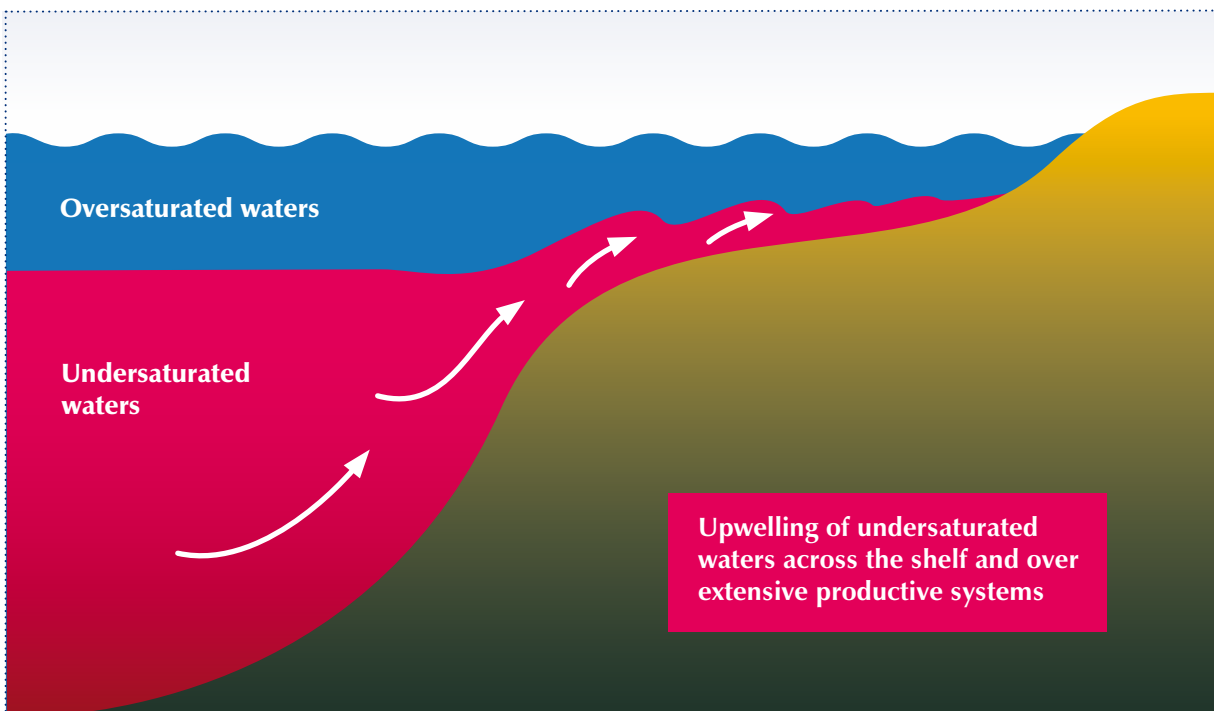
Coastal regions periodically experience upwelling events where deeper ocean water circulates onto continental shelves and near-shore areas. This exposes productive upper ocean ecosystems to colder water containing more nutrients but also more CO₂.

often cause undersaturated water to well up and flow to the shore. Coastal marine organisms that form shells are unaccustomed to such events, and periodic exposures to these significantly different conditions may affect these communities. Upwelling of undersaturated water is already occurring on the west coast of North America, and it may start to occur elsewhere where ocean conditions allow.

As ocean acidification makes the upper oversaturated layer of sea water shallower each year, these natural upwelling events will more

Seasonal invasion of undersaturated waters such as is already occurring on the west coast of North America could have serious impacts on important fisheries such as the oyster industry.

Source after Carol Turley based on Feely *et al.*, *Science* (2008).



Learning from history

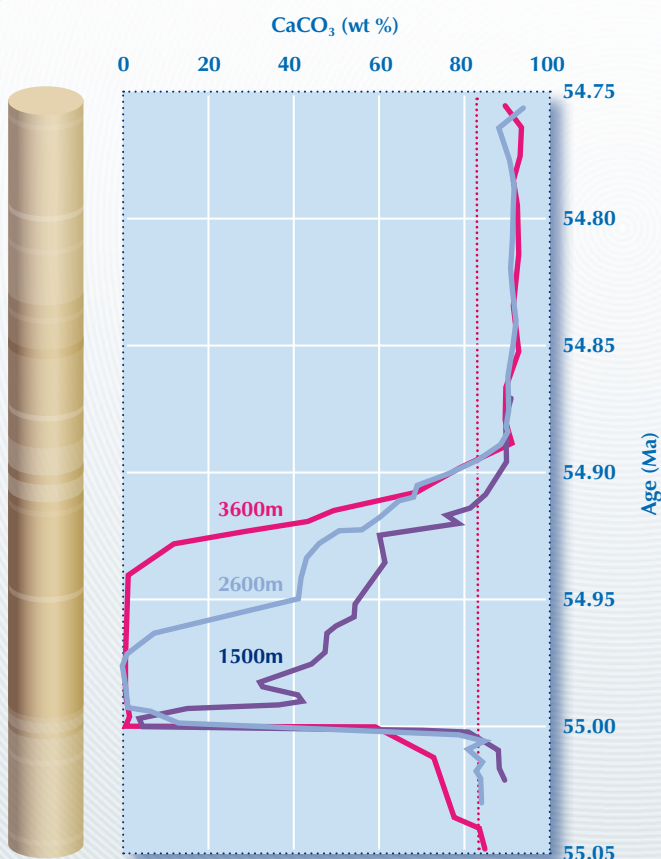
The chemistry of the Earth's ocean has not always been constant and there have been periods in the distant past where the ocean has been more acidic. So what can we learn from these previous ocean acidification events, and can we use these to help predict the severity of future impacts stemming from the current episode of ocean acidification?

What can past events of ocean acidification teach us?

In the recent history of the Earth the acid/base balance of the ocean has been relatively constant. This knowledge comes from both being able to indirectly measure the pH of the ocean and to calculate it from the bubbles trapped in ice and being able to examine past conditions using records preserved in the Earth's glaciers and sediments.

Deep sea cores from the South Atlantic for different palaeodepths show how at the time of the PETM the calcite saturation horizon shoaled by over 2km in just a few thousand years, and then took ~100,000 years to recover to pre-PETM levels. This event is potentially a contributing factor to the mass extinction of benthic foraminifera at this time.

Source after Zachos et al., *Science* (2005).



Air bubbles trapped in glaciers provide a vital record of past atmospheric conditions.



Photo © Ulf Rehsell, IFM-GEOMAR

History from the ice

Air bubbles trapped in ice sheets provide a record of past atmospheric CO₂ levels from which ocean pH can be calculated. Long cores extracted from the ice can be 'read' somewhat like tree rings: surface layers reflect recent conditions while deep ice layers were deposited long ago. Such ice core records show that over the last 800,000 years until the mid-1800s, atmospheric CO₂ levels were never more than 280ppmv, generating a sea water pH of 8.2. Current atmospheric CO₂ concentrations are ~390ppmv and ocean surface water pH is now 8.1.

Distant similarities

Further back in history there were long periods and abrupt events where ocean pH was lower than even today's conditions. What can these previous events tell us about what we now face? The most frequently discussed event occurred 55 million years ago in the Cenozoic Era (the Palaeocene-Eocene Thermal Maximum (PETM)). This dramatic event in Earth's history saw global temperatures rise by around 6°C (11°F) over less than 10,000 years, with a corresponding rise in sea level as the ocean warmed. Atmospheric CO₂ concentrations rose, causing the depth of calcium carbonate saturated water to become much shallower. The event was possibly linked to a large input of carbon into the system due to ocean warming, which oxidized in the sea water to form CO₂ which gassed-off into the atmosphere.

This period may help us understand what the future may hold for us. Although many of the benthic deep water calcifiers died out, some claim that because surface-dwelling marine species survived the conditions 55 million years ago, they should survive perfectly well through our current ocean acidification event. The danger of this claim is that it ignores the primary, fundamental difference between the PETM and today: these ocean acidification events span vastly different timescales. Today's event is

Making it clear

happening over a few centuries, while back at the PETM change took place over a period of around 10,000 years.

Degrees of difference

The reason why the present situation differs so markedly is largely because of the fast rate of change of atmospheric CO₂ levels versus the slow rate of geological processes that remove CO₂ from the atmosphere. The important difference is that in all of the past ocean acidification events in the last 65 million years the CO₂ was added slowly over thousands of years and in some cases hundreds of thousands of years from volcanic activity. The ocean had ample opportunities to complete full, millennial-scale mixing cycles where surface waters could circulate through to the deep ocean and back. The result was that the carbonate sediments on the sea floor began to dissolve and release carbonate ions that helped neutralize some of the acidity. The ocean of millions of years ago also contained much higher calcium and magnesium ion concentrations than are present in the ocean today, which helped to stabilize calcium carbonate minerals in marine animals' skeletons so they were better able to tolerate the acidified conditions than they are able to do in today's ocean.

Today, atmospheric CO₂ levels are increasing considerably faster than the ocean water can mix, forcing these processes out of alignment. The result is that most CO₂ is building up in a layer of sea water near the ocean surface. About 50% of all the CO₂ we have emitted resides in upper 10% of the ocean. The ability of sediments to regulate ocean chemistry and neutralize the acidity is simply too slow – taking place over more than 1000 years – and so ocean pH and the amount of available carbonate ions are now declining.

Coral reefs in places such as the Seychelles support an amazing diversity of life, and could be seriously affected by 2050 if the current rate of ocean acidification continues.

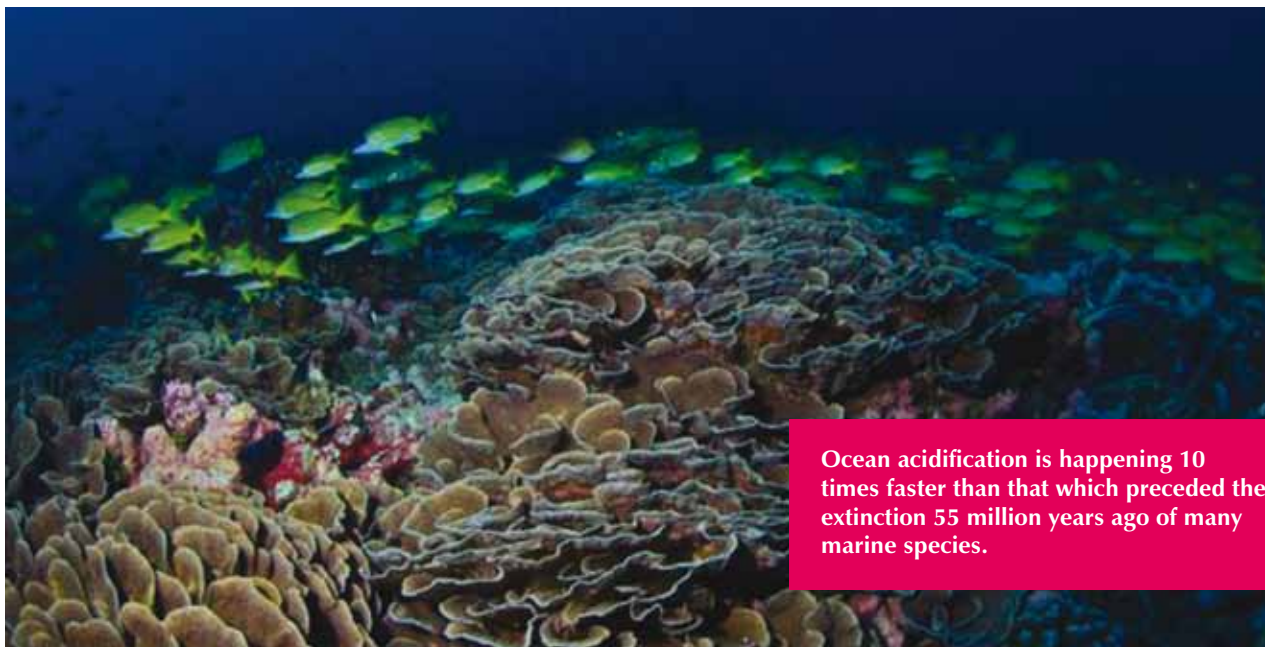


Photo: © Jerker Tammerander

Can the past be a guide to the future?

It is possible to compare what is happening now with what happened many millions of years ago when the ocean was more acidic. Acidification today is occurring faster and to a greater extent than anything seen in the fossil record over the past 65 million years. It is estimated for example that ocean acidification is happening 10 times faster than that which preceded the extinction 55 million years ago during the Palaeocene Eocene Thermal Maximum, the largest ocean acidification event since the extinction of the dinosaurs. Sediment cores from the sea floor of the south-east Atlantic Ocean show a dramatic change in composition due to the dissolution of carbonate organisms leaving just the red clay. This is the result of increased levels of acidity that drove many deep ocean living species with calcium carbonate bodies to extinction. From the sea floor cores it appears that it took more than one hundred thousand years for the oceans to recover.

Ten times faster

Over Earth's history, ocean life has recovered from numerous sudden extinction episodes by adaptation and evolution of new species, but the time scales for extinction and repopulation are millions of years, not a few hundred years. Human-driven ocean acidification is affecting the ocean far faster than the Earth's natural recovery pace can accommodate. Today's rate of acidification is 10 times faster than anything experienced since the demise of the dinosaurs 65 million years ago.

Ocean acidification is happening 10 times faster than that which preceded the extinction 55 million years ago of many marine species.

Can we predict the future severity of ocean acidification?

It is inevitable that atmospheric CO₂ levels will rise from the current level of 391 ppmv, and this will continue to decrease surface sea water pH. However, the rate and extent of any future increase is difficult to predict because it depends on whether we cut our emissions of CO₂ and if we do by how much. If the increase in atmospheric CO₂ continues unabated, by the end of the 21st century it is possible that these concentrations will have reached 800ppmv and ocean pH will have dropped by a further 0.3 – 0.4 units, equivalent to a further 150 – 200% increase in hydrogen ions.

There is less certainty, however, on possible biological impacts from ocean acidification because we have not experienced such changes and different groups of marine organisms appear to be more or less sensitive to changing sea water chemistry.

Life-long impacts

For many marine organisms, their gametes, larval stages, juveniles, and adults may be affected differently by ocean acidification; thus, it is important to consider the life-cycle impacts on survival and reproduction. In general, studies suggest that early stages (gametes, larvae, and juveniles) are expected to be sensitive to ocean acidification. Stress usually limits the performance of organisms – for example, stressed organisms grow slower and smaller, predators will be less effective

Retrieving a midwater box trawl sampling for pteropods in the Antarctic.



Photo © John M. Baxter

and prey perhaps less able to avoid capture. For adults, stress caused by ocean acidification may affect performance and will ultimately reduce their rates of growth and reproduction. Even though individuals may survive, reduced reproductive capacity can result in fewer progeny so that populations are affected too.

Amongst those species threatened by ocean acidification are tropical and deep-sea corals, calcareous plankton and free-swimming pteropods where changing conditions will make building and maintaining their skeletons and shells more difficult. These species play key roles in the ocean either

Corals – complex issues

Coral host tiny single-celled algae called zooxanthellae within their cells which through their photosynthesis are an important source of carbon for the coral and for coral calcification (skeleton building). The coral-algal relationship is delicately balanced and if the algae do too well and their numbers greatly increase, the transfer of carbon to the coral host can be disrupted. So even if the single-celled algae photosynthesis were to increase under high CO₂, this wouldn't necessarily be good for the coral hosts. However, even though studies have shown that the photosynthesis of some other species of algae is enhanced by the levels of CO₂ projected for the end of this century, about 700-800 ppmv, zooxanthellae photosynthesis has not been shown to significantly increase at this CO₂ level. Experiments have shown that in most cases there is a decrease in coral calcification rate when the CO₂ level increases, so it is clear that the rise in CO₂ is actually decreasing the corals' ability to build their skeletons and hence their ability to withstand storms rather than protecting them. What this means is that reef growth will eventually be less than natural reef erosion and reefs will decline.



Coral reefs are vital but fragile ecosystems extremely sensitive to ocean acidification.

Photo © Dan Laffoley

A lobster's tale

One experimental study has showed that shell mass of several crustaceans including lobster, reared in culture for 60 days, actually increased with increased CO₂, while another showed that the shell growth of lobster larvae was reduced. This underlines the need to study the whole life cycle as well as the physiological health of the organisms. Without more study, it is premature to say that crustaceans will be 'safe' from ocean acidification for two principal reasons.

1) Shell-making requires energy, but each organism only has a finite energy budget, so the increased shell mass almost certainly occurs hand-in-hand with reduced energy for other functions like growth and reproduction. These factors were outside the scope of this study, so ocean acidification's effects on the overall health and longevity of these organisms is still unknown.

2) Lobsters (and crustaceans in general) have a different type of shell and a different mechanism for growing their shells from molluscs and corals. Lobster shells are exoskeletons containing a large proportion of chitin along with calcium carbonate minerals, and they are shed periodically instead of added to continuously. When preparing to moult, lobsters are thought to remove a lot of the minerals from old shells and preserve them in their bodies to deposit into the new skeleton later.

It is presently unclear whether this difference in growth mechanism will affect how lobsters respond to ocean acidification.



Lobster.

Coralline algae such as *Lithothamnion topiiforme* are likely to be among the most sensitive organisms to ocean acidification.



because they build three-dimensional structures, such as coral reefs, which host a considerable biodiversity and act as coastal protection, or because they are key components of the marine food chain and the ocean's biogeochemical cycles (e.g. calcareous plankton, pteropods).

Winners and losers

The growth and level of photosynthesis of certain marine phytoplankton and plant species may increase with higher CO₂ levels, but this is by no means a general rule. For others, higher CO₂ and rising acidity may have either negative or neutral effects on their physiology. Therefore, particular marine plants will be 'winners', while others will be 'losers' and some may show no signs of change. Some of the experiments that have been done so far suggest that the likely new dominant phytoplankton and plant species in the future acidified ocean may be less able to support the productive, diverse food chains that we presently rely on to support healthy ocean ecosystems and fisheries resources.

Exposing the consequences



Photo © Jason Hall-Spencer

Lush seagrass beds devoid of epiphytes thrive in naturally low pH sea water.

Although it is difficult to precisely forecast the consequences of ocean acidification because there remain so many unknowns about human behaviour and ocean ecosystems' responses, we can learn from history what the likely outcome will be, and we can look at areas of the ocean that have been subjected to natural long-term acidification.

Communities of organisms found at cold water volcanic CO₂ vents on the sea floor (not the extremely hot deep-sea vents) with lower pH than predicted for the next few decades show that certain species of microalgae, seaweeds and seagrasses can grow very well in such areas, but in comparison to other similar areas, not subject to reduced pH levels, overall biodiversity is reduced and shell corrosion is evident.

Won't species simply adapt to ocean acidification?

It can be expected that as sea water pH and carbonate levels continue to fall there will be 'winners' and 'losers' in ocean ecosystems, but it is inevitable that marine communities will change. The animals and plants most likely to be affected first are those that have calcium carbonate-based shells or skeletons. Organisms can respond to harmful changes in their environment in one of three ways: they can acclimate, adapt or go extinct.

Projections for atmospheric CO₂ and surface global mean pH difference from pre-industrial levels for various IPCC 2007 emission scenarios indicating some experimentally determined biological impacts and the years when the first localised seasonal occurrence of aragonite undersaturation is projected to occur. Source after Turley et al., *Marine Pollution Bulletin* (2010).

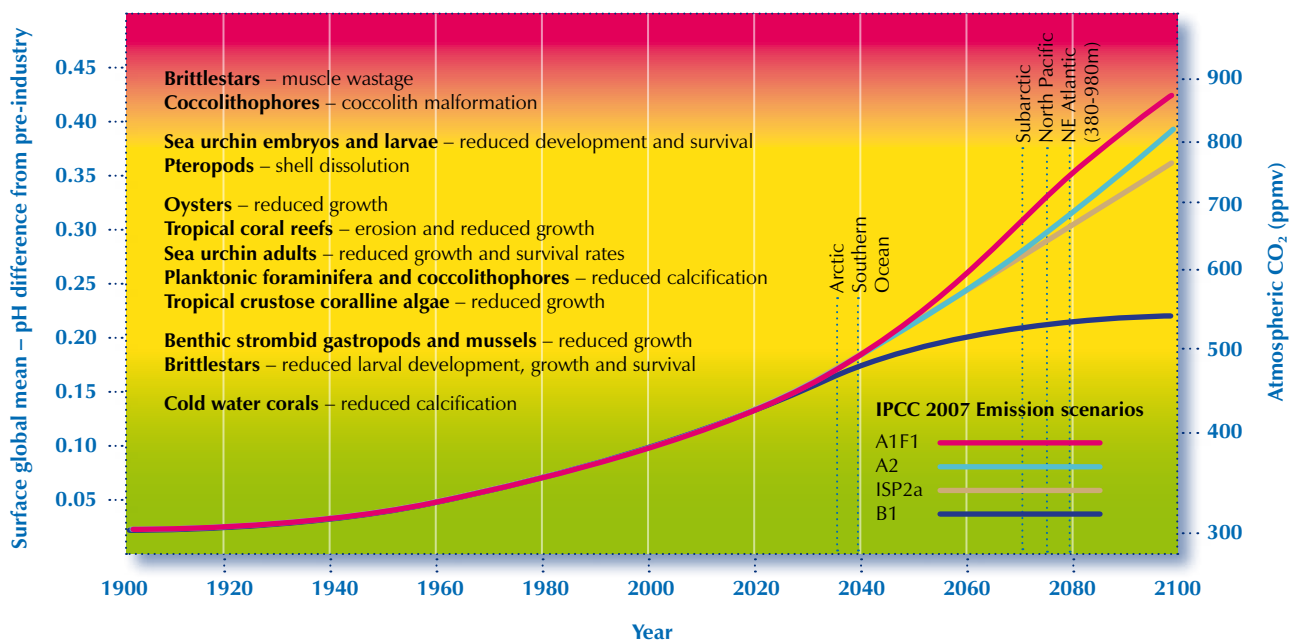




Photo © Jason Hall-Spencer

As pH and carbonate levels continue to fall there will be 'winners' and 'losers' – but change is inevitable.

Seabed community in area of Mediterranean Sea with bubbles from volcanic CO₂ vents makes an ideal natural laboratory for studying ocean acidification.

Natural high CO₂ laboratories

Most species possess some capacity to acclimate. All species have a certain ability to tolerate changing conditions, although the resulting increased stress may affect their ability to compete in their environment. An organism's ability to conduct essential activities depends on its energy budget.

If an organism spends more energy maintaining protective shells or a protective skeleton, it will have less energy for other vital functions like reproduction or growth. Similarly, if an organism without a shell spends more energy breathing and excreting waste in a higher-CO₂, lower-pH ocean, it may have less energy for seeking food or other important survival activities.



Severely eroded limpet shell from a naturally high CO₂ area.

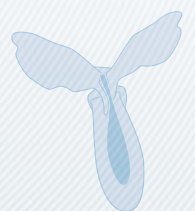


Photo © Jason Hall-Spencer

Coral polyps introduced to an area of naturally low pH showing erosion of their calcareous skeleton.



Photo © Jason Hall-Spencer



Key survival processes – how will ocean acidification affect whole organism physiology?

Source after Carol Turley.

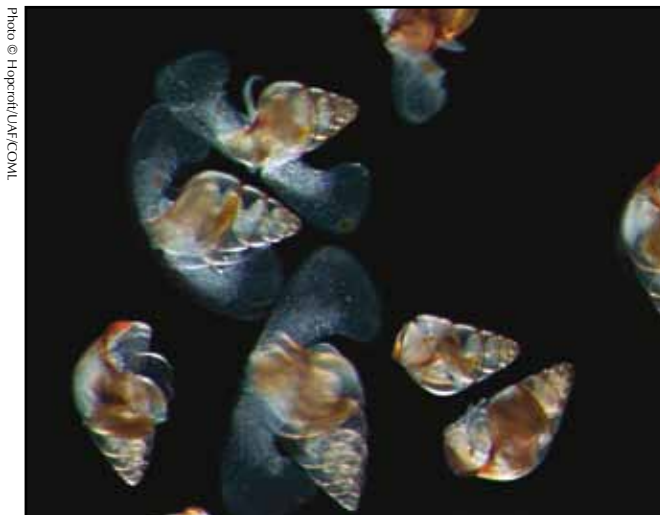
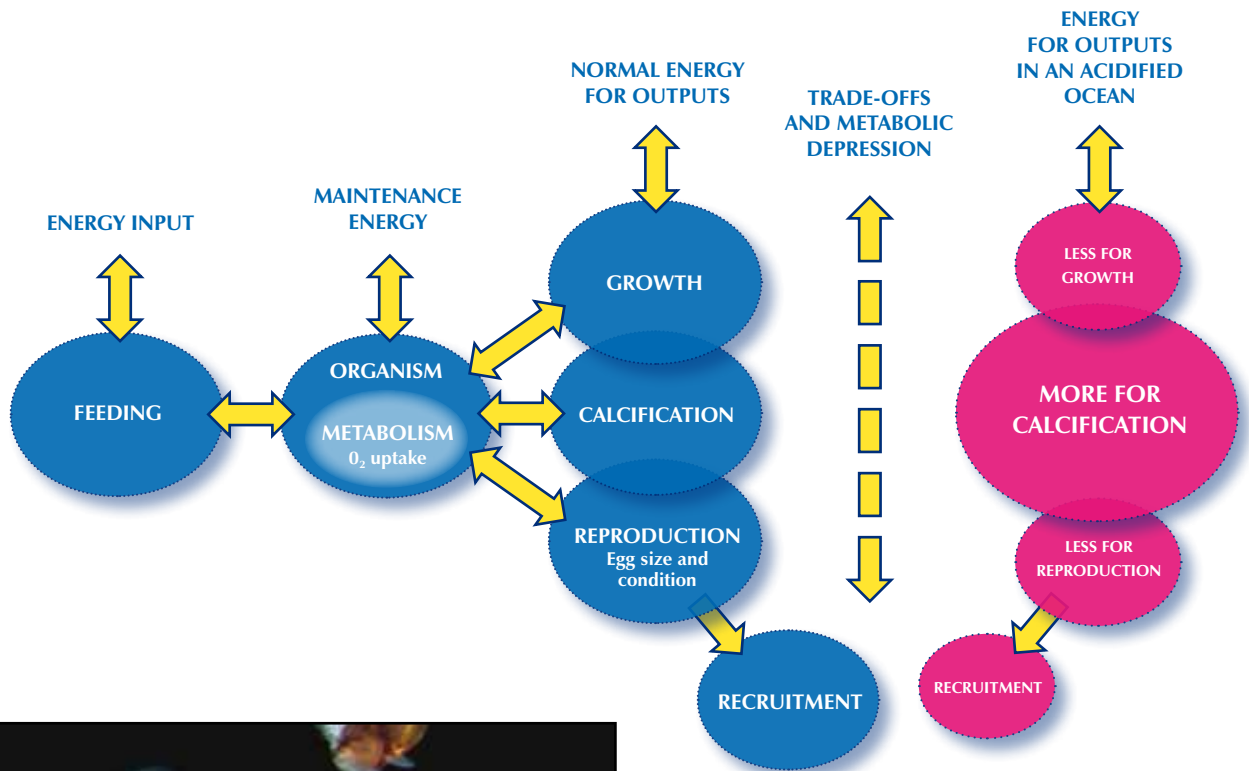


Photo © Hoptcroft/UAF/COML

The tropical pteropod *Limacina bulimoides*.

Speed of change

Species can adapt to environmental change as small genetic variations emerge that make some individuals more suited to the new conditions. Short-lived species potentially have a greater capacity to respond to rapid environmental change, because generation times are short, each new generation experiences conditions only slightly different from the preceding one, and because there are a greater number of individuals which can develop helpful variations. In comparison, long-lived species tend to have far less capacity to adapt quickly. However, the changes that are already being observed in shell thickness of pteropods, which have an annual life-cycle, illustrates that even for relatively short-lived species the current rate of change in ocean pH may be too fast for them to be able to adapt. More research will be needed to confirm this is the case.

Previous acidification events in the geological record were often associated with extinctions of many species. Whilst the cause of such extinction episodes is often complex, it is notable that the recovery took hundreds of thousands and, after mass extinctions, millions of years.

An acidification arms race?

The key question is not whether ocean life on the whole will adapt and evolve in response to ocean acidification. What is questionable is its ability to adapt and evolve quickly enough in the face of 'rapid' ocean acidification and to do so in such a way that the 'new' communities that arise are able to provide the same essential goods and services that we use and that support us.

Keeping pace with change

Evidence from the current distribution of coral reefs is that it is related to the ocean's saturation state with respect to aragonite and that they could keep up with the pace of naturally changing conditions. It is highly unlikely that they may be able to adapt to the acceleration in changing conditions predicted in the next few decades.

Understanding our options

The effects of ocean acidification will increase incrementally and although the impacts that are already apparent are relatively minor, they are growing along with the rate of acidification. Furthermore, there is a lag between CO₂ emissions and reaching an equilibrium state, so even if emissions were to be capped and subsequently reduced the pH of the ocean would continue to fall for some time to come. A reduction in atmospheric CO₂ levels is essential if we are to first reduce, then halt ocean acidification before it is too late.

Would cutting emissions of CO₂ make a difference?

Over the past 250 years, atmospheric CO₂ levels have increased by nearly 40% from 280 ppmv to 391 ppmv today, and this level continues to rise at about 2 ppmv per year. The levels of atmospheric CO₂ have been tempered by the ocean's uptake of CO₂ (which causes ocean acidification) and would otherwise today be close to 460 ppmv, a level that would have led to even greater climate change.

Fossil fuel use continues to increase atmospheric CO₂ levels.



Reversible in the long term

Although we are already seeing changes in ocean water chemistry as a result of the absorption of atmospheric CO₂ and impacts of this on marine ecosystems, these changes are reversible in the long term. Any such reversal would, however, be dependent on a significant reduction over a prolonged period in atmospheric CO₂ levels. Reducing the emissions of CO₂ from the burning of fossil fuels, cement manufacturing and deforestation are the only realistic ways of beginning to achieve such a reduction.

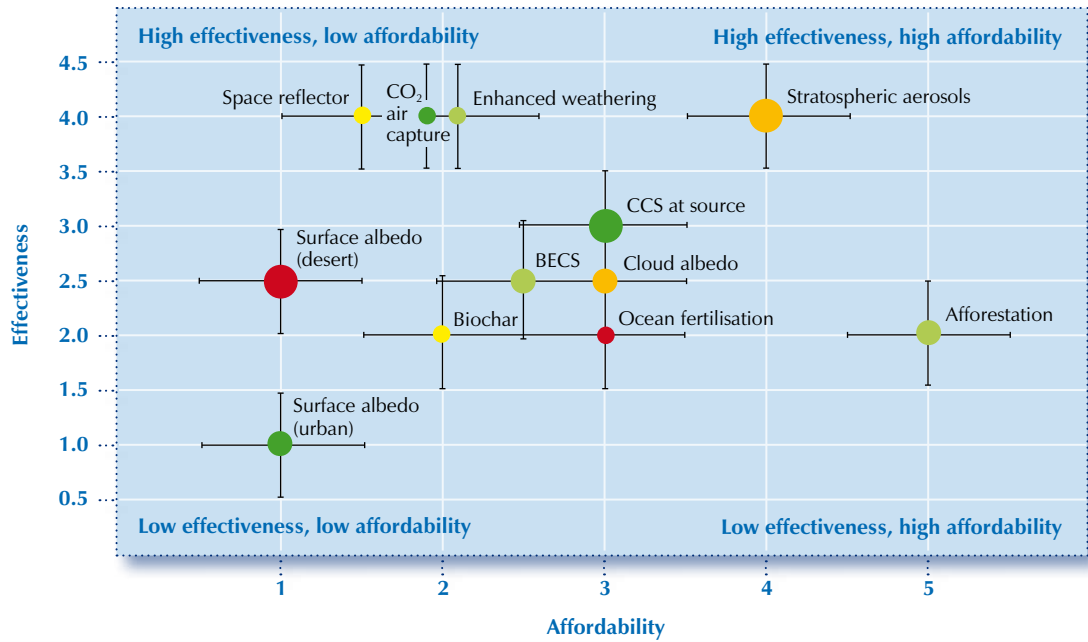
The level at which atmospheric CO₂ concentrations will peak is predicted to be well above 400 ppmv and the effects on ocean pH will continue to be seen for some considerable time after any reduction in atmospheric CO₂ levels is achieved. The CO₂ absorbed by the surface waters of the ocean will continue to penetrate into the deep ocean for the next few centuries.



Halting deforestation would help reduce the rate of increase of atmospheric CO₂ levels.



There are few current geoengineering options for tackling climate change that are both highly effective and highly affordable. Only carbon capture and storage (CCS) would have any impact on atmospheric CO₂ levels. A green dot represents a safer option than those with a high risk shown in red; the size of the dot indicates their timeliness (large if they are rapidly implementable and effective, small if they are not). Black bars indicate the degree of uncertainty concerning affordability (horizontal) and effectiveness (vertical). Source after The Royal Society *Geoengineering the Climate* (2009).



The development of marine renewable energy technologies are vital to help reduce CO₂ emissions from fossil fuel burning.

Photo © John M Baxter



Not too late

Some changes resulting from ocean acidification are already being seen and more are likely, even if rapid steps are taken to cap and significantly reduce atmospheric CO₂ levels in the next few years. It is not too late, however, to begin to try and minimize further damage. The technological and economic means are available to significantly reduce CO₂ emissions if we choose to do so. The longer we take to act, the greater the ultimate impacts will be, and the greater the legacy of ocean acidification will be.

Can we solve ocean acidification with geoengineering?

The concept of geoengineering is the deliberate manipulation of the Earth's climate. Most proposed geoengineering approaches to limit climate change impacts attempt to relieve the symptoms of climate change without addressing the root cause of the problem – excess CO₂ in the atmosphere. As such they fail to address the chemical consequences of these emissions. For example, strategies that seek to cool the Earth by reflecting additional sunlight into Space would have little direct effect on ocean chemistry and therefore would not significantly diminish threats posed by ocean acidification.

Unknown consequences

There have been proposals to diminish changes in ocean chemistry by adding compounds to the ocean that would chemically neutralize acids. The main problem with these approaches is that the amount of material that would need to be added is very large. In fact it has been calculated that the amount that would be needed is something more than the tonnage of CO₂ we have already emitted to the atmosphere. Thus, these proposed solutions would require a new and significant mining and chemical processing infrastructure with unknown environmental consequences.

It has also been suggested that ocean fertilization could help reduce climate change and ocean acidification. The fertilization would stimulate phytoplankton growth, resulting in a net increase in the biological uptake of atmospheric CO₂. Reducing the concentration of atmospheric CO₂ near the ocean surface would decrease surface ocean dissolved inorganic carbon concentrations.

Global ocean carbon cycle models predict that with fixed emissions of CO₂ to the atmosphere, ocean fertilization would have a moderate mitigating effect on ocean acidification near the surface but would cause further acidification in the deep ocean, as sinking organic particles are decomposed back to CO₂ at greater depths. If emissions of atmospheric CO₂ continue to rise the deep ocean would continue to acidify. The scale and longevity of the effort that would be required for such approaches would be cost-prohibitive, and the benefits would be minimal at best.

Prevention better than cure

Many observers have concluded that the resources that could be spent on geoengineering would be better applied to transforming our energy system – preventing CO₂ from entering the environment in the first place rather than attempting to neutralize its effects after it is already spreading through the atmosphere and oceans.

Online guide

Download a copy of this new guide to ocean acidification and learn more about this issue at: <http://www.epoca-project.eu/index.php/Outreach/RUG/>

What is the Ocean Acidification Reference User Group?

A key challenge is ensuring that ground-breaking science on issues such as ocean acidification addresses the questions that need to be answered and that these answers get quickly and effectively into the hands of policy advisers and decision makers so that action can be taken. The Ocean Acidification Reference User Group (RUG) draws on UK, European and international experience in fast-tracking the exchange of information between scientists and end users.

The RUG was established in 2008 to support the work of the European Project on Ocean Acidification (EPOCA), and now supports complementary studies in Germany (BIOACID) and the UK (the UK Ocean Acidification Research Programme), with strong links in similar processes in the USA. The RUG draws together a wide range of end users to support the work of leading scientists on ocean acidification, to facilitate the rapid transfer of knowledge, and help the effective delivery of quality science.

This guide draws on the experience of the RUG, coupled with the knowledge of the leading experts on ocean acidification, to provide an introduction for policy advisers and decision makers on this most critical and urgent of issues.

The RUG is formed of representatives from: Alfred Wegener Institute of Polar and Marine Research, BP Euro-Mediterranean Center on Climate Change (CNRS), Canadian Tourist Industry Authority, Centre National de la Recherche Scientifique (CNRS), Climate Central (Princeton University), Conservation International, Department for Food, Environment and Rural Affairs (Defra), Department of Energy and Climate Change (DECC), Directorate of Fisheries (Norway), European Science Foundation (ESF), Fondazione Eni Enrico Mattei (FEEM), Greenpeace, International Atomic Energy Agency, International Geosphere-Biosphere Programme (IGBP), International Union for the Conservation of Nature (IUCN), Laboratoire des Sciences du Climat et de l'Environnement (LSCE), Leibniz Institute of Marine Sciences (IFM – GEOMAR), Marine Institute (Ireland), Natural

England, Observatoire National sur les Effets du Réchauffement Climatique (ONERC), Plymouth Marine Laboratory (PML), Potsdam Institute for Climate Impact Research (PIK), Rolls Royce, Royal Institution, Scientific Committee on Oceanic Research (SCOR), Scottish Natural Heritage (SNH), Shellfish Association of Great Britain (SAGB), Stockholm Resilience Center, The Nature Conservancy, UK Climate Impacts Programme (UKCIP), UNEP World Conservation Monitoring Center, Universitat Autònoma de Barcelona (UAB), The Worldwide Fund for Nature (WWF).

Observers

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Further details and contacts

Further details on the work of the Ocean Acidification Reference User Group and the European Project on Ocean Acidification can be found on our website:

<http://www.epoca-project.eu/index.php/Outreach/RUG/> and the UK Programme at www.oceanacidification.org.uk

For BIOACID please see <http://www.bioacid.de/>

If you have any further enquiries please contact us at: policyguide-epoca@obs-vlfr.fr



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This document borrows from *Frequently Asked Questions about Ocean Acidification*, www.who.edu/OCB-OA/FAQs representing the latest scientific consensus on the answers to 37 detailed questions. The following scientists contributed responses to that document:

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We are also grateful to the following that provided the multilingual translations:

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Chinese: Vera Shi, Hui Lui, Guang Gao and Kunshan Gao.

French: Stéphanie Reynaud, Eric Béraud, François Simard and Jean-Pierre Gattuso.

Spanish: Juancho Movilla, Elisa Fernandez-Guallart, Carles Pelegero and Marta Estrada.

We thank them all for helping disseminate this information beyond English speakers.

Please cite this document as: Ocean Acidification Reference User Group (2010). Ocean Acidification: Questions Answered. Laffoley, D. d'A., and Baxter, J.M. (eds). European Project on Ocean Acidification (EPOCA). 24 pp.

The guide was produced with financial support from Prince Albert II of Monaco Foundation, Scottish Natural Heritage, Natural England, IUCN, EPOCA and the UK Ocean Acidification Research Programme, and is based on best practice communication approaches pioneered by the UK's Marine Climate Change Impacts Partnership.

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