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CHANGE



The Ocean in a High-CO₂ World

The Second Symposium on Ocean Acidification

Back in 2004 the Scientific Committee on Oceanic Research and the Intergovernmental Oceanographic Commission held the ground breaking international symposium *The Ocean in a High-CO₂ World* that brought ocean acidification as an important anthropogenic CO₂ issue to the forefront of research. Important outputs were a report on future research needs, a communications policy, and heightened concern about the possible consequences of ocean acidification on marine organisms and the food webs that depend on them. Since then, research into ocean acidification has grown and it has been communicated so widely that it was reported as a new finding by the IPCC in their 4th Assessment on Climate Change (2007) only three years later. IGBP was one of the sponsors [1] of the 2nd symposium on *The Ocean in a High-CO₂ World* held on 6-9 October 2008 at the Oceanography Museum of Monaco under the High Patronage of His Serene Highness Prince Albert II. The increase in sponsors itself is an indicator of the growing concern of the international science community.

The meeting doubled the attendance of 2004, bringing together 220 scientists from 32 countries to reveal what we now know about the impacts of ocean acidification on marine chemistry and ecosystems, to assess these impacts for policy makers, and to decide what the future research needs are. The three science days reported on what had been learned in the last four years from all aspects of this rapidly emerging research issue — from future scenarios of ocean acidification, effects of changes in seawater chemistry on nutrient and metal speciation, palaeo-oceanographic perspectives, mechanisms of calcification, impacts on benthic and pelagic calcifiers, physiological effects from microbes to fish, adaptation and micro-evolution, fisheries and food webs, impacts on biogeochemical cycling and feedbacks to the climate systems. The science days consisted of invited and submitted papers, discussion sessions on future research priorities and a large poster display, all of which offered an intensive symposium in the wonderful Oceanography Museum, set

Photo credit: Jean Louis Teyssie, IAEA



James Orr together with HSH Prince Albert of Monaco at the Symposium.

high over Monaco overlooking the blue waters of the Mediterranean Sea and close to numerous restaurants where discussions continued on into the evening. A *Report on Research Priorities* has been completed and a subset of the science results from the Symposium will be reported in a special issue of the

peer-reviewed journal *Biogeosciences*.

On the fourth day there was a session for policy makers and the press which consisted of a summary of the science findings from the symposium, and presentations on the potential socio-economic impact of ocean acidification and on engaging with policy makers. To better achieve this, in addition to the science outputs, a *Summary for Policymakers* is being prepared. HSH Prince Albert II not only supported the Symposium, but also addressed those present, recognizing the important scientific challenges of ocean acidification and called on climate change policy makers all over the world to recognize that CO₂ emissions must be reduced urgently and drastically in order to prevent serious impacts of ocean acidification on marine organisms, food webs and ecosystems.

Rather than alleviate the concerns that emerged from the meeting four years ago, the symposium brought home our worst fears about how serious the issue of ocean acidification is, and will be, as we continue burning fossil fuels. It was recognized that marine scientists of all disciplines must convince the climate change negotiators to take ocean acidification seriously, particularly in this important year when negotiations at COP-15 [2] take place in Copenhagen in December. A suggestion from the floor that we produce a conference declaration, was widely supported.

The Monaco Declaration has been carefully crafted based on the symposium findings, and was launched on 30 January 2009, receiving wide media coverage. It has been signed by 155 of the conference participants. If you have five minutes, read it, if not read the extracts below:

Ocean acidification is underway ... is already detectable ... is accelerating and severe damages are imminent ... will have socioeconomic impacts ... is rapid, but recovery will be slow. ... Ocean acidification can be controlled only by limiting future atmospheric CO₂ levels.

Despite a seemingly bleak outlook, there remains hope. We have a choice, and there is still time to act if serious and sustained actions are initiated without further delay. First and foremost, policymakers need to realize that ocean acidification is not a peripheral issue. It is the other CO₂ problem that must be grappled with alongside climate change. Reining in this double threat, caused by our dependence on fossil fuels, is the challenge of the century. Solving this problem will require a monumental world-wide effort. All countries must contribute, and developed countries must lead by example and by engineering new technologies to help solve the problem. Promoting these technologies will be rewarded economically, and prevention of severe environmental degradation will be far less costly for all nations than would be trying to live with the consequences of the present approach where CO₂ emissions and atmospheric CO₂ concentrations continue to increase, year after year.

Products from the Symposium

IGBP's research on ocean acidification is conducted in collaboration with SCOR, primarily by IGBP Core Projects SOLAS, IMBER and PAGES. The Second Symposium on the Ocean in a High-CO₂ World, in collaboration with SCOR, the Intergovernmental Oceanographic Commission (IOC) and the International Atomic Energy Agency (IAEA), resulted in a number of products, aimed at different audiences:

- Research priorities report on ocean acidification
- The Monaco Declaration
- A special issue of the journal *Biogeosciences*
- *Oceanography* magazine article (in preparation)
- Press Releases
- Fact Sheet
- Summary for Policymakers (in preparation)

All publications, when completed, are available from <http://ioc3.unesco.org/panet/HighCO2World.html> and can be accessed from the "Ocean in a High CO₂ World" page of the portal www.ocean-acidification.net

Fortunately, partial remedies already on the table, if implemented together, could solve most of the problem. We must start to act now because it will take years to change the energy infrastructure and to overcome the atmosphere's accumulation of excess CO₂, which takes time to invade the ocean.

Therefore, we urge policymakers to launch four types of initiatives:

- to help improve understanding of impacts of ocean acidification by promoting research in this field, which is still in its infancy;
- to help build links between economists and scientists that are needed to evaluate the socio-economic extent of impacts and costs for action versus inaction;
- to help improve communication between policymakers and scientists so that i) new policies are based on current findings and ii) scientific studies can be widened to include the most policy-relevant questions; and
- to prevent severe damages from ocean acidification by developing ambitious, urgent plans to cut emissions drastically.

An example to illustrate the intense effort needed:

To stay below an atmospheric CO₂ level of 550 ppm, the current increase in total CO₂ emissions of 3% per year must be reversed by 2020. Even steeper reductions will be needed to keep most polar waters from becoming corrosive to the shells of key marine species and to maintain favourable conditions for coral growth. If negotiations at COP-15 in Copenhagen in December 2009 fall short of these objectives, still higher atmospheric CO₂ levels will be inevitable.

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Endnotes

1. The symposium was again sponsored by SCOR and IOC-UNESCO as well as the IAEA-Marine Environment Laboratories and IGBP. Additionally, it was supported financially by the Prince Albert II Foundation, the Centre Scientifique de Monaco, the U.S. National Science Foundation, the International Council for the Exploration of the Sea, the North Pacific Marine Science Organization, the Oceanography Museum, and the Monaco Government.
2. The overall goal for the 2009 (COP15) United Nations Climate Change Conference is to establish an ambitious global climate agreement for the period from 2012. COP stands for Conference of Parties and is the highest body of the United Nations Climate Change Convention consisting of environment ministers who meet once a year to discuss the convention's developments. Ministers and officials from around 189 countries and participants from a large number of organizations will take part.



The Ocean in a High-CO₂ World

Science highlights from the symposium

Reef development in a high-CO₂ world: Coral reefs of the eastern tropical Pacific

Many coral reefs in the eastern tropical Pacific develop at slow – or even marginal – rates: they grow slowly and erode quickly. This has been blamed on the upwelling of cold, nutrient-rich waters to the surface that can depress calcification and stimulate bioerosion. Our study suggests that the increased carbon dioxide content of the upwelled water, which lowers the pH and depresses the aragonite (CaCO₃) saturation state, is also an important factor in the poor reef development. We verified the low saturation state of waters from the eastern Pacific (Galápagos, Gulf of Chiriquí, and Gulf of Panamá), and then compared coral samples from nearby reefs with samples from the Bahama Islands, a region with high aragonite saturation state. The Bahama samples contained abundant inorganic aragonite cements that tend to fill the pore spaces within corals and the reef, while the eastern Pacific samples contained few

to none. The lack of cements are thought to reduce the resistance of the corals and reefs to bioerosion; in fact, bioerosion rates in the eastern Pacific are ten times those of other reef regions. This study shows that increasing atmospheric carbon dioxide, which lowers the aragonite saturation state of seawater, threatens not only the coral calcification rates, but also the reef-structures that support high biodiversity and protect shorelines [1].

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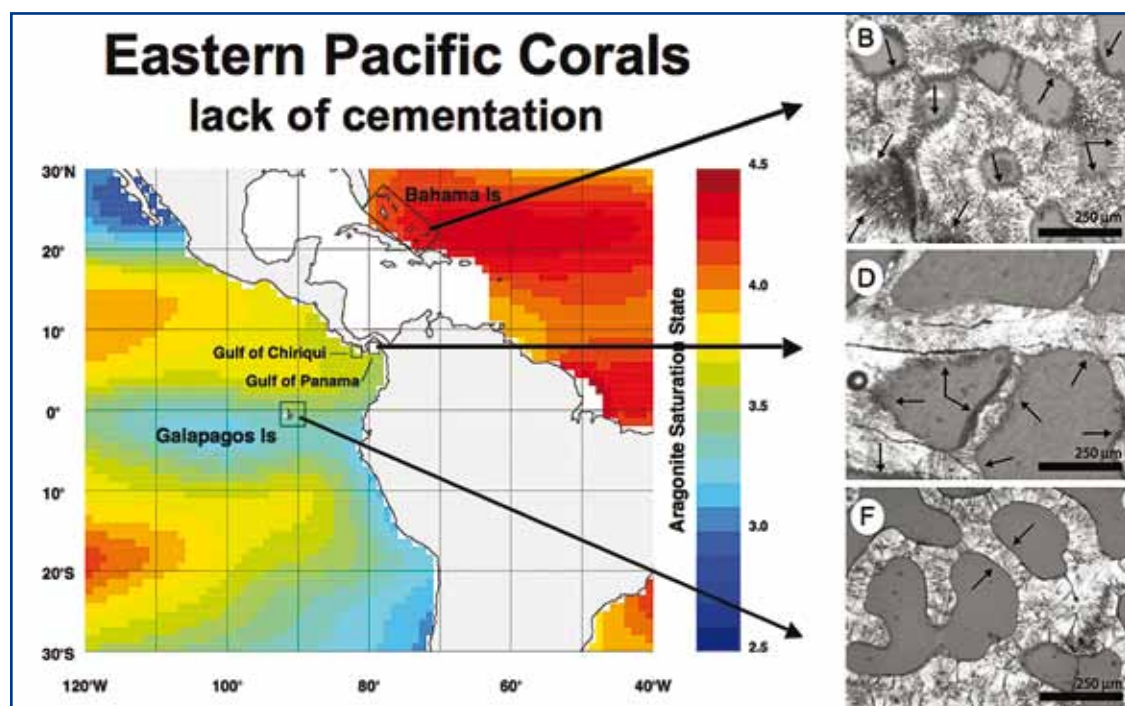
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Carbonate cements within the pore spaces of corals from areas with naturally different CO₂ levels. The Galapagos sample (where seawater is similar to what is expected for the rest of the tropics with a tripling of atmospheric CO₂) contains no cement. The absence of cement is evidenced by a clearly defined boundary between the inner skeletal wall and open pore space. This is contrary to the sample from the Bahamas (where seawater has very low CO₂ levels) – the boundary between the skeletal wall and pore space is blurred by the abundance of cements. Minor amounts of cement are present from the intermediate CO₂ environment from Pacific Panama, but these are still trivial relative to the Bahamas.

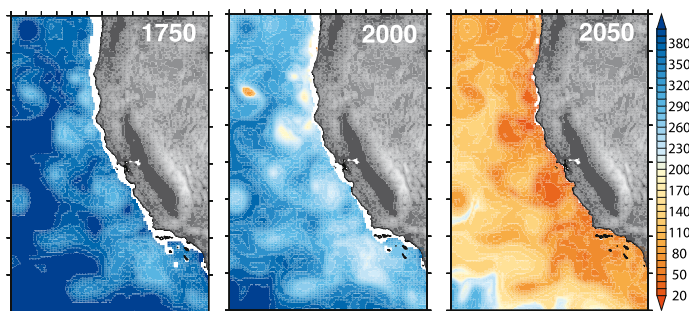
High vulnerability of eastern boundary upwelling systems to ocean acidification

Eastern boundary upwelling systems, such as the California Current, are particularly sensitive to ocean acidification: the pH of their surface waters is already comparatively low and their change in pH for a given uptake of anthropogenic CO₂ is particularly high. Eddy-resolving simulations [1] for the California Current System show that between pre-industrial times and present, the mean pH of the surface ocean has decreased by about 0.1 pH units. As a result, the aragonite saturation horizon has shoaled by ~100 m, bringing waters corrosive to calcifying organisms into the surface (euphotic) zone in a few eddies and in near-shore environments during upwelling (Figure). The model data agree with recent observations. Projections for 2050 (IPCC SRES A2-scenario) suggest an additional drop of pH by ~0.2 units and a widespread and year-round shoaling of the saturation horizon into the euphotic zone. Due to the high temporal and spatial variability that characterizes eastern boundary upwelling systems, organisms are exposed to a wide range of pH (variations of up to 0.3 to 0.4 units) and saturation states, making it difficult to define when critical thresholds are crossed. At the same time, these systems may today offer opportunities to study the response to organisms to low and varying pH and saturations states likely to be widely experienced in the future.

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Model simulations of the shoaling of the aragonite saturation horizon (depth in m) in the California Current from 1750 to 2050 (snapshots for the month of August). White areas depict saturated (non-corrosive) waters to the sea floor.

Footnote

1. Produced with the ETH-UCLA Regional Oceanic Modeling System.

Changes in the carbonate system of the global oceans

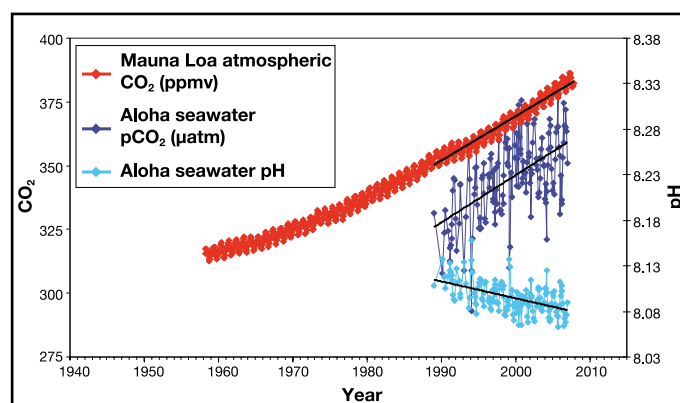
Increasing atmospheric carbon dioxide is rapidly changing seawater chemistry as a result of the acidifying effects of CO₂ on seawater. This acidification makes it more difficult for marine organisms (e.g., corals, plankton, calcareous algae, and molluscs) to build skeletons and shells of calcium carbonate. Impacts on these calcifying organisms will lead to cascading effects throughout marine ecosystems. Repeated hydrographic cruises and modelling studies in the Atlantic, Pacific and Indian oceans show evidence for increased ocean acidification. The dissolved inorganic carbon increases in surface waters of the Pacific Ocean over the past 15 years are consistent with pH decreases (Figure). These changes can be attributed, in most part, to anthropogenic CO₂ uptake by the ocean. These data verify earlier model projections that ocean acidification is occurring as a result of the uptake of carbon dioxide released by the burning of fossil fuels. From these results we estimate an average upward migration of the aragonite saturation horizon of approximately 1-2 metres per year in the Pacific and Indian oceans. Thus making water corrosive to calcifying organisms that are closest to the surface.

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Time series of atmospheric CO₂ at Mauna Loa and surface ocean pH and pCO₂ at Ocean Station Aloha in the subtropical North Pacific Ocean. Mauna Loa data: Dr. Pieter Tans, NOAA/ESRL; HOTS/Aloha data: Dr. David Karl, University of Hawaii (modified after Feely, 2008).

Reference

Feely, R A (2008) Ocean Acidification. In: State of the Climate in 2007, Levinson D H and Lawrimore J H (eds.). Bull. Am. Meteorol. Soc., 89(7): S58.

Salmon pHisling in the North Pacific Ocean

The northern North Pacific is home to salmon populations that have sustained human societies throughout their history in the region. Salmon are potentially linked to CO₂ emissions by one of their prey, a marine snail or shelled pteropod called *Limacina helicina*. The shells of this mollusk are made of the aragonitic form of calcium carbonate (CaCO₃), which may begin to dissolve as the oceans acidify so that their fate as a component of the holoplankton is potentially threatened by an increasingly acidic ocean. What if pteropods simply disappeared from the North Pacific? During the 20th century they received little attention from the scientific community but they were found routinely in salmon diets. Historical data reveal considerable variability in where and when they are important as prey. During the last five decades, chum salmon (*Oncorhynchus keta*) stomachs from the northwestern Pacific contained about 15-25% pteropods and this trend has been increasing. During the 1960s in the Gulf of Alaska, humpback salmon (*O. gorbuscha*) stomachs contained about 15% pteropods on average in April. The current situation is poorly known as studies of salmon ecology are rare in this part of the Pacific, but if pteropods continue to form a component of salmon diets, it is likely that ocean acidification will increasingly affect this food source.

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Sockeye salmon haul off the Canadian coast in the mid 1980s.

Insert: Chum salmon caught in the high seas of the North Pacific Ocean.

Consequences of ocean acidification for fisheries

Ocean acidification can affect fish both directly through physiological processes and indirectly through changes in the marine food webs, such as food quality, quantity and availability, and through the deterioration of fish habitats, such as tropical and deep-sea coral reefs. Alone, or in combination with other factors, ocean acidification can affect reproduction, growth and mortality in fish populations. Early life stages, hence recruitment of young fish into the fish stock, may be particularly vulnerable. This is bad news because recruitment governs the dynamics of fish stock biomass. Observations and model predictions of ocean acidification show that the changes occur faster and are stronger in high latitude oceans. This can have significant consequences on fisheries in the north Pacific and Atlantic that hold some of the most important fish stocks in the world, among them Alaska pollock, Atlantic herring, blue whiting, and north-eastern Arctic cod. The collapse of fish stocks is most likely to occur when overfishing coincides with unfavourable environmental conditions that reduce recruitment. Institutions responsible for fisheries management need to be adaptive and respond quickly to new environmental knowledge, enabling them to maintain healthy and robust fish stocks that are not overfished and have suffered a minimum loss of genetic diversity. This can secure a high potential for adaptation to changes in the environment.

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Cod in a deep-water coral habitat at 200 m depth. The NE-Arctic cod stock is one of the few cod stocks that so far have not been fished down due to mismanagement. But problems may soon come: the cod lives in a high latitude ecosystem that will experience significant ocean acidification within a few decades. Modelling predicts that deep-water coral reefs off the coast of Norway may meet undersaturated conditions within this century. Photo: Jan Helge Fosså and Pål B. Mortensen, Institute of Marine Research, Norway.

Impact of ocean acidification on underwater sound

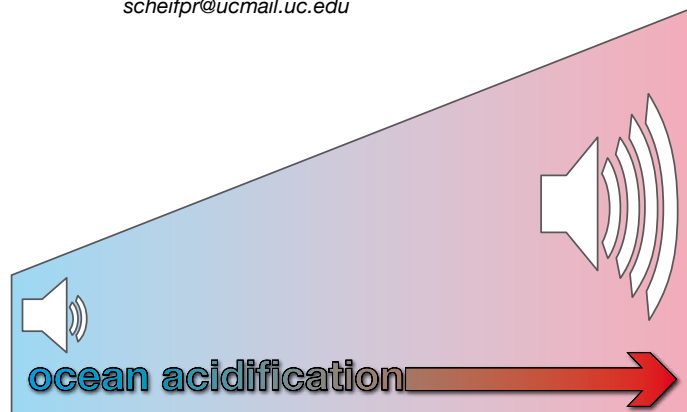
Thirty years ago, scientists trying to determine the absorption of low frequency sound in seawater in order to develop new navy sonar systems, discovered, somewhat surprisingly, that this absorption is pH dependent: the lower the pH the less the absorption. Today this discovery has an implication for ocean acidification: as the ocean acidifies it will become noisier! Lower absorption (the pH change predicted in a recent Royal Society Report [1] would cut the absorption in half) will result in a smaller propagation loss which means that at a given distance from a noise source (such as a ship's propeller) the sound level will be louder than it previously was. It is presently the subject of legal contention whether noise levels can cause significant distress to marine mammals but if there is a problem ocean acidification could make it worse. As with other predicted effects, the absorption change would have the greatest impact soonest in specific situations. For example underwater sound typically propagates along the axis of a naturally occurring sound channel – in many areas this axis is over 1,000 meters deep which means that it would take a significant time for pH change to work down the water column. In some locations such as the North Pacific Ocean, however, a shallow secondary sound channel exists where the impact should be observed sooner. For a more detailed explanation of the ocean chemistry see: Hester K. C., E. T. Peltzer, W. J. Kirkwood, P. G. Brewer. "Unanticipated consequences of ocean acidification: A noisier ocean at lower pH", *Geophysical Research Letters*, 35: L19601 (1 October 2008).

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Acidification of the ocean results in a noisier ocean.

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The early development of oysters: synergistic effects of ocean acidification and temperature

Studies have found that projected elevations in atmospheric carbon dioxide (CO_2), as early as 2065, will reduce the calcification of adult organisms in oceanic environments. Less is known, however, about how the combined effects of elevated dissolved CO_2 ($p\text{CO}_2$) and temperature will impact the sensitive early development stages of marine organisms. In a series of studies, we investigated the synergistic effects of elevated $p\text{CO}_2$ (375, 600, 750 and 1000 ppm) and temperature (18, 22, 26 and 30 °C) on the fertilisation, development and growth of the early life history stages of two ecologically and economically important estuarine molluscs, the Sydney rock oyster, *Saccostrea glomerata*, and the Pacific oyster, *Crassostrea gigas*. We found that exposure to elevated $p\text{CO}_2$ and temperature had deleterious effects on the reproduction, growth and development of the early life history stages of *S. glomerata* and *C. gigas*. Overall as $p\text{CO}_2$ increased and temperature deviated from 26 °C, fertilisation, development and growth decreased and abnormality and mortality increased (Figure). Furthermore, *S. glomerata* was more sensitive to elevated $p\text{CO}_2$ and temperature than *C. gigas*. This implies that if our oceans continue to acidify and warm, the Pacific Oyster, *C. gigas*, may become the dominant species along the South Eastern coast of Australia.

Laura Parker received the prize for the best student oral presentation at the Symposium.

Laura M. Parker

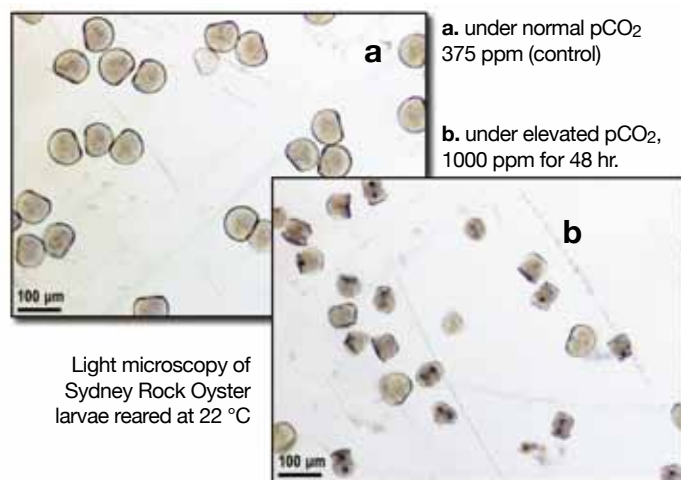
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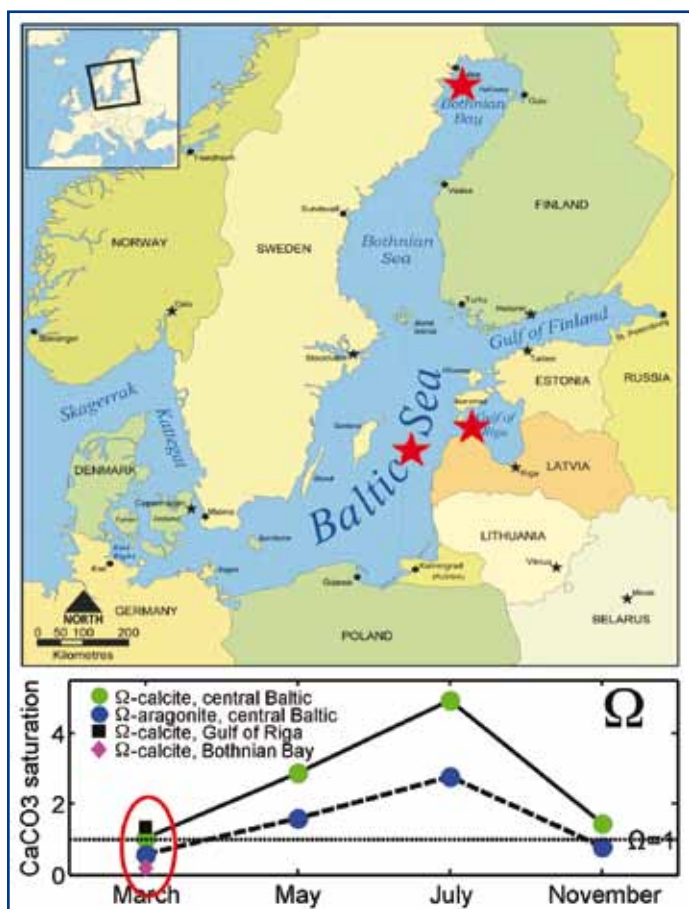
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Light microscopy of Sydney Rock Oyster larvae reared at 22 °C

Low winter CaCO_3 saturation in the Baltic Sea: consequences for calcifiers

Ocean acidification lowers the calcium carbonate (CaCO_3) saturation state (Ω) of seawater and thus the ability of calcifying organisms to form shells or skeletons. All surface oceans are presently supersaturated with respect to CaCO_3 ($\Omega > 1$) but under continued emissions of CO_2 this will change. The first oceans to experience surface undersaturation ($\Omega < 1$) will be the Arctic and Southern Oceans, and it will most likely occur in wintertime, the time of the year at which Ω is typically lowest. Measurements in the Baltic Sea show that a similar situation already pertains there: the central Baltic becomes undersaturated (or nearly so) in winter, with respect to both aragonite and calcite mineral forms of CaCO_3 (Figure). Undersaturation appears even more severe in the most northerly part of the Baltic Sea, the Bothnian Bay. Low wintertime Ω is matched by unusual patterns of chemical etching (dissolution) of CaCO_3 shell fragments in sediments. We are taking advantage of this natural analogue to better understand future impacts of ocean acidification, by comparing biogeographical distributions of calcifying organ-



Calcium carbonate saturation state of Baltic seawater over the seasons. $\Omega < 1$ indicates undersaturated waters where carbonate dissolution occurs.

Map: Norman Einstein

isms in the Baltic with carbon chemistry (mindful that there are also strong gradients in salinity and other parameters). For instance, while many calcifiers are scarce in the Baltic, the blue mussel *Mytilus edulis* occurs even in the low Ω Bothnian Bay.

Toby Tyrrell

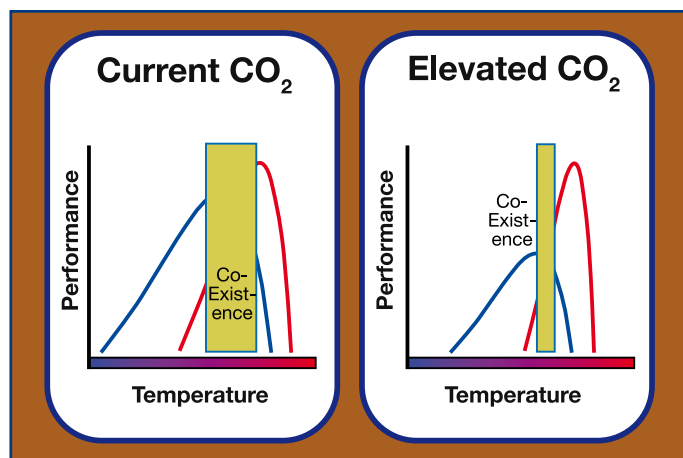
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Mechanisms linking climate to ecosystem change: physiological background and ecological implications

Climate change causes ocean warming and acidification on global scales. In contrast to well established effects of warming, evidence for the effects of rising carbon dioxide (CO_2) on marine ecosystems is only just emerging. However, future scenarios also indicate threats to marine life through combinations of rising CO_2 levels, warming and more frequent oxygen depletion (hypoxia) in the ocean. There is a need to understand the causes and effects of realistic future climate scenarios on ecosystems. We need to identify key physiological mechanisms and their responses to combined effects of progressive acidification, warming and hypoxia. In the changing ocean, these are physiological mechanisms which define species performance, including their capacity to interact, e.g. in food webs [1]. Many current ecosystem changes likely occur when ambient temperature drifts beyond the species-specific temperature limits of survival (thermal



Conceptual model of CO_2 dependent effects on species interactions at ecosystem level (modified after [1]). Species differ in their thermal windows of performance and coexist where these windows overlap (left). Changes in species interactions are elicited by warming and also by the specific sensitivity of species to ocean acidification under elevated CO_2 levels. The narrowing of thermal windows and differential loss of performance will affect coexistence ranges, relative performance, and thus the patterns of competition and susceptibility to predation (right).

tolerance window) and causes a shift in phenology resulting in the species no longer being able to survive in this location. High sensitivity to elevated CO₂ levels may involve a low capacity for acid-base regulation, as seen in lower marine invertebrates [2]. The disturbed extracellular acid-base status affects processes involved in growth, calcification, neural functions, blood gas transport and behavioural capacities [2]. Metabolic pathways shift to new equilibria. Current evidence indicates elevated sensitivity to higher CO₂ levels towards the extremes of thermal windows [3]. The ultimate consequence may be a narrowing of thermal tolerance windows and associated ranges of geographical distribution and of the performance at ecosystem level. Thus, CO₂ may exacerbate warming effects on marine ecosystems. Future research will have to test these concepts under realistic climate and ocean acidification scenarios and in various marine ecosystems between the tropics and the poles.

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Impact of ocean acidification on marine snails and deep-sea corals

The impact of ocean acidification on calcification has been investigated for over 20 years. However, few taxonomic groups of calcifying organisms have been studied in acidified conditions: among them are reef-building corals and phytoplankton (coccolithophores). Yet, there are more than 16 phyla of calcifying organisms, some of them critically important due to their role in biogeochemical cycles or because they are host to ecosystems with high biodiversity.

Arctic pteropods, or marine snails, and deep-sea corals thrive in areas that will be among the first affected by changes in ocean acidification. The polar pteropod *Limacina helicina* (Figure 1) is a major dietary component for zooplankton and higher predators such as herring, salmon, whale and birds. Its fragile aragonite shell plays a vital protective role and forms an external skeleton. Perturbation experiments, carried out under controlled pH conditions represen-

tative of carbonate chemistry for 1990 and 2100, show calcification rates decreased by 28% for the pteropod *L. helicina* when pH was lowered by 0.3 units. An even larger reduction of 50% was seen in response to a decrease of 0.3 pH units for the cold-water coral *Lophelia pertusa* (Figure 2). While tropical coral reefs are formed by a large number of coral species, the structure of a cold-water coral reef is made by one or two coral species that form the basis of a very diverse ecosystem. A reduction in skeletal growth as a consequence of ocean acidification can therefore become detrimental to the whole ecosystem.

These first results presented during the Monaco Symposium raise great concern for the future of pteropods and cold-water corals, and organisms that depend on them as a food source or habitat. One role of the recently launched national or international research projects on ocean acidification will undoubtedly be to generate data on other taxa, longer time scales and on the interactive impacts of ocean acidification and other global changes such as temperature on these organisms.

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Figure 1. The Arctic pelagic snail (pteropod) *Limacina helicina* (surface water, Spitsbergen).



Figure 2. The cold-water coral *Lophelia pertusa* (150 m depth off the Hebrides in the North Atlantic)

Natural CO₂ vents reveal ecological tipping points due to ocean acidification

Investigation into the long-term biological effects of permanent exposure to high CO₂ concentrations in a natural ecosystem has taken research into ocean acidification an important step forwards. Effects were studied on rocky and sedimentary marine communities around underwater volcanic vents that release millions of litres of CO₂ per day. The vents lacked the poisonous sulphur compounds that characterise many vents. The high CO₂ levels had major impacts on marine life including 30% reductions in species diversity at average pH 7.8, compared with normal seawater (pH 8.1).

This work provides the first confirmation of modelling and short-term laboratory experiments which predict severe reductions in the ability of marine organisms to build shells or skeletons from calcium carbonate due to the dramatic effects of CO₂ on seawater chemistry. Seagrasses thrived at increased CO₂ (Figure) levels but major groups such as corals, sea urchins and calcified algae were removed from the ecosystem and replaced by invasive species of algae. Such studies will help us to predict the future effects of ocean acidification and demonstrate, for the first time, what happens to marine ecosystems when key groups of species are killed due to rising CO₂ levels.

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Venting of CO₂ at a Mediterranean site provides the opportunity to observe changes in ecosystems along gradients of decreasing pH close to the vents. Sea grasses and brown algae grow well at the vents but groups such as sea urchins, coralline algae and stony corals are killed by the acidified water.

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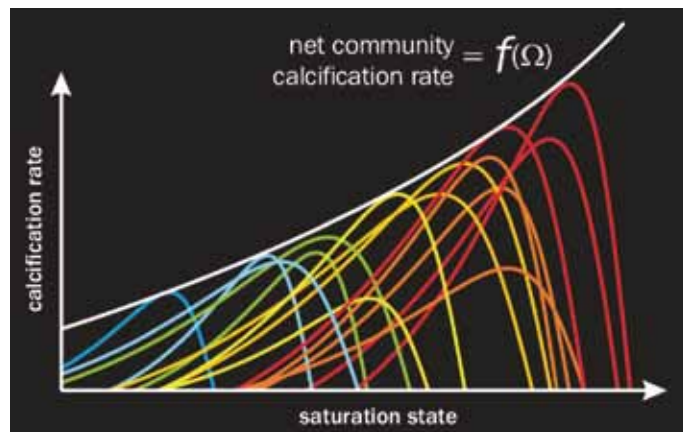
From the lab to models: algal calcification and ocean acidification

Global modellers are called upon to predict the future uptake of fossil fuel carbon dioxide (CO₂) by the ocean. The impact of ocean acidification on marine calcifiers may be important in this calculation, so we construct model parameterizations for plankton carbonate production based on biological experiments. However, for a major carbonate producer in the open ocean, algae called coccolithophores, no consistent calcification response to acidification (pH) is apparent in laboratory studies. This gives us a real headache – how to write a single equation for wildly differing experimental responses? Which, if any, is the “correct” response? Two clues may help: firstly, a peak in calcification is observed in some experiments, hinting at an environmental pH “optimum” for this process. Secondly, in manipulations of more complete ecosystems such as mesocosms (large partly submersed bags) and shipboard incubations of seawater samples, calcification is consistently lower in more acidic conditions (higher CO₂). The existence of pH optima for calcification would allow the use of the same quasi-empirical trick as we already employ for modelling the response of algal growth rate to temperature – the “Eppley curve”. Marine ecosystems may then be expected to respond to future acidification in an analogous way to increasing temperature – by gradual transition in dominance from more to less heavily calcified coccolithophores and progressively reduced carbonate production globally, as illustrated below.

See the full article in Ridgwell et al. (2009) *Biogeosciences* 6 (2): 3455-3480.

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Potential ecosystem level response of carbonate production with increasing acidity – a simplification based on individual pH optimum curves for different (hypothetical) species of calcifying phytoplankton

Economic impacts of ocean acidification: costs and savings

Stringent mitigation of further carbon dioxide (CO₂) emissions seems more feasible now that the costs have been projected as relatively low. Transforming the worldwide energy system to meet a 450 ppm CO₂-equivalent target would cost only 0.5% to 2% of the GDP, our global gross domestic product [1], [2], [3]. At the same time, the findings of the ocean acidification community add to the overall conclusion that CO₂ impacts have been under-estimated in the past. Both of these observations imply sharper emission cuts than had been foreseen.

With the estimate of a potential development of carbon markets and international agreements to cap CO₂ emissions, a price tag can now be assigned to the acidification-driven degradation of the ocean's large capacity to absorb CO₂. The ocean's current carbon uptake may soon represent an annual subsidy to the global economy of about 0.1 to 1% GDP. However, any fraction of the ocean's uptake leads to degradation through ocean acidification, which in the future would imply an economic loss in proportion to the damage this causes, thus adding another slice to the overall costs of CO₂ emissions.

The upcoming years will witness a heated debate on the adequate mix of mitigation technologies, such as sub-seabed CO₂ sequestration or massive-scale deployment of solar thermal power, in view of costs and risks. The ocean acidification community could supply some of the necessary metrics for a rational discourse on how to judge the risks of CO₂ leakage after sub-seabed CO₂ sequestration against the benefits from reduced atmospheric CO₂ concentration.

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Ocean acidification: connecting the science to policy

Over the last ten years the political and public awareness of the many consequences of the increase in greenhouse gas emissions to the planet's climate has increased dramatically. The complexity of many of the issues that we face means that it is a great challenge for anyone to be an expert or even well-informed about everything, and there is a very real danger that some issues may be overlooked. Ocean acidification is one such issue, but most certainly one where we can't afford for this to happen.

Our understanding of the chemistry and physics of these processes is increasing and evidence is growing of the biological consequences of a declining seawater pH. The key is to communicate these findings to the policy makers and decision takers in such a way that the key messages can be received and understood and that action results.

Cooperation and communication are needed at all stages between the scientists and policy-makers. Scientists, by nature, are curious and look to answer the interesting and intriguing questions that will stretch the boundaries of our knowledge and understanding. This is good and laudable but in order to generate action to address the issues that threaten the oceans it is ever more important to distinguish between what we would like to know and what we need to know. Providing answer to the latter is what is required to make the connection between science and policy.

Where there is a large programme of work it is possible to make such a connection through the establishment of a Reference User Group that provides an interactive forum throughout the lifetime of the project where the researchers and the 'policy customers' can exchange ideas. This guides scientists to consider how their research can answer questions that need to be addressed to reach key policy decisions. Complex answers must be presented in an accessible manner whilst not detaching these from the underlying science. The UK Marine Climate Change Impacts Partnership Annual Report Card (ARC) is an example of how this can be successfully done and the 2009 ARC (publication in April) seeks to demonstrate the complex and linked relationships between various aspects of climate change, including ocean acidification, that policy makers must take into account.

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