OCEAN ACIDIFICATION

The oceans of the world are natural carbon reservoirs. As the oceans absorb atmospheric CO_2 they buffer the extent of global climate change. This is the good news. The bad news is that this service comes at a cost: the chemical balance of the oceans is changing at a rapid and unprecedented rate, with serious implications for marine biodiversity, ecosystem services and livelihoods. Known as "ocean acidification", it is a direct consequence of increasing atmospheric CO_2 concentrations that is occurring independently of climate change.

Current picture

The world's oceans have largely been left out of the mainstream discussion of global climate change. Yet, as one of the largest natural reservoirs of carbon, the surface ocean plays a critical role in the global carbon cycle.

The global atmospheric concentration of anthropogenic carbon dioxide (CO_2) has increased from a pre-industrial value of approximately 280 parts per million (ppm) to approximately 387 ppm in 2009, with half of this increase occurring within the last 30 years. Without the uptake of CO_2 by the oceans, atmospheric CO_2 levels would be even higher (by some 55 ppm) than they are at present, and the effects of global climate change would be more marked.

Oceans have absorbed one quarter to one third of the CO_2 emitted to the atmosphere from the burning of fossil fuels, deforestation and other human activities since 1800. As more and more CO_2 has been emitted, the ocean has absorbed greater amounts at increasingly rapid rates. This has resulted in a change in the chemical balance of seawater known as "ocean acidification".

Science behind ocean acidification

Gases are readily exchanged between the air and the sea. As a result, the ocean is one of the largest natural reservoirs of carbon, absorbing more than a quarter of anthropogenic CO2 emissions each year. Once absorbed, CO2 dissolves to form carbonic acid, which then dissociates into bicarbonate and hydrogen ions. The more hydrogen ions there are in the water the lower is its pH, i.e., the more acidic it is.[1] Importantly, excess hydrogen ions react with, and eliminate, carbonate ions, which are necessary for calcium carbonate skeleton and shell production in many marine organisms. Carbonate ions are now less abundant than at any other time in the last 800,000 years.

The surface waters of the oceans are normally slightly alkaline—with a pH greater than 7. The oceans remain alkaline today, but they are 30 per cent less so than they are estimated to have been at the start of the industrial revolution. The term "ocean acidification" refers to this progressive slide by the oceans down the pH scale, away from alkalinity and toward acidity.

Like climate change, ocean acidification is a direct consequence of increasing atmospheric CO_2 concentrations. It is, however, a *different process occurring independently of climate change,* which is the product of a number of greenhouse gases causing the Earth to absorb more of the sun's energy.

Interestingly, however, the solubility of gaseous CO_2 is dependent on temperature: CO_2 is more soluble in colder water than in warmer water. It follows that the cold surface waters of high latitude oceans, which accumulate a higher concentration of CO_2 than others are being hit hardest and earliest by ocean acidification and will be the first to experience significant changes.

Why it matters to biodiversity

Increasing ocean acidification reduces the availability in seawater of carbonate minerals such as calcite and aragonite, which are necessary for skeleton and shell formation in corals,

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**This series provides a synopsis of issues relevant to the Rio Conventions.
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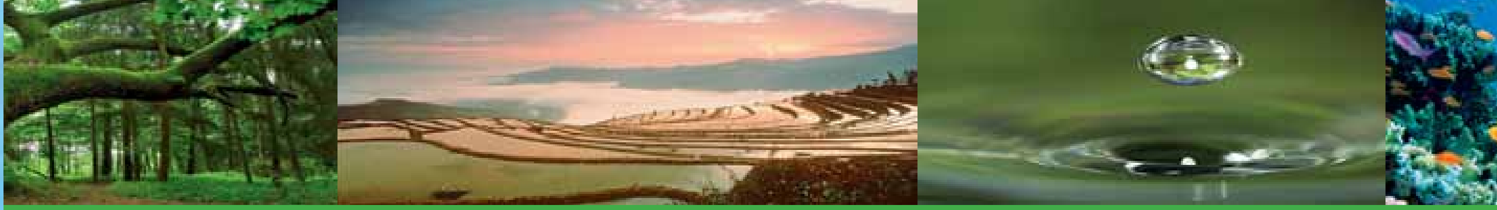

shellfish and marine plankton. When seawater is under-saturated with these minerals, it becomes corrosive, making it harder (more energy costly) for marine organisms to form shells and skeletons, and weakening or dissolving those that have already been formed. As a result, ocean acidification will affect the physiology, development and survival of these organisms.

Effects on ocean life

The many marine organisms that use carbonate minerals to form shells and skeletons include crustose coralline algae, some phytoplankton, warm- and cold-water corals and a range of invertebrates from small snails to lobsters. These organisms represent important components of the marine food chain in almost all ecosystems, from tropical regions to high latitudes and the deep sea.

Ocean acidification is expected to have particularly negative impacts on the calcification rate of reef-building stony corals. While warm-water corals may suffer from reduced calcification (an important barometer of health in reef ecosystems), it is expected that cold-water corals will suffer first. According to predictions, 70 per cent of known cold-water coral ecosystems could experience corrosive water conditions by 2100, and some by as early as 2020.

A trend towards more acidic conditions is expected to result in weaker skeletons and slower growth rates, which will make it more difficult for corals to retain a competitive advantage over other marine organisms. Increasingly brittle coral skeletons are at greater risk of storm damage and bioerosion, which will reduce the structural complexity of reef systems. This in turn will reduce the quality and diversity of habitats that reefs provide for other marine organisms and the extent to which they protect coastlines against waves and storm surges. Figure 1 illustrates the impacts of ocean acidification on reef-building corals.

Figure 1: Analogs of the ecological structures predicted through three coral reef scenarios of increasing CO2 and temperature, as shown. The atmospheric concentration of CO2 and temperature increases shown are those for the scenarios and do not refer to the locations photographed. **A.** Reef slope community at Heron Island. **B.** Mixed algal and coral communities associated with inshore reefs around St. Bees Island near Mackay. **C.** Inshore reef slope around the Low Isles near Port Douglas. *Source:* Hoegh-Guldberg, O., et al. (2007). Coral reefs under rapid climate change and ocean acidification. Science 318, 1737–1742.

Some bottom-dwelling organisms, such as echinoderms, molluscs and crustaceans, also depend on carbonate minerals for their survival and effective functioning. Reduction in growth rates, size and body weights, impaired fertility and embryonic development and shell dissolution can all be expected as a result of exposure to acidified water. Figure 2 shows the severely corroded, pitted shells of two gastropod (snail) species in a naturally acidified site.

Figure 2: P. caerulea and H. truculus showing severely eroded, pitted shells in naturally acidified areas of minimum pH 7.4.
Source: Hall-Spencer, J. M., et al. (2008). Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. Nature 454:96–99.

Many shelled organisms are located at the bottom or the middle of global ocean food webs. Their loss to ocean acidification, therefore, will alter predator–prey relationships, and the effects will be transmitted throughout the ecosystem, disrupting large components of the marine food web. A loss or change in biodiversity could have significant ecological consequences.

In contrast to those in the terrestrial biosphere, marine ecosystems have evolved in a comparatively homogenous environment under relatively stable conditions and over evolutionary timescales. Even subtle changes in environmental conditions may therefore have major effects on ecosystem functioning, with yet unforeseen consequences for the continued ability of the ocean to provide key goods and services upon which human populations depend.

Changes in ocean acidity may affect the population size, dynamics and community structures of marine calcifiers in favour of those that rely less on calcium; it will negatively affect shellfish; it will impact fish; it may benefit highly invasive non-native algal and invertebrate (such as tunicate) species; and it will reduce coral calcification. While the initial impact of ocean acidification is relatively clear, however, its eventual impact will depend on the complex interaction of many other variables.

Effects on human well-being

The oceans provide numerous ecosystem services that benefit humankind. Coral reefs are particularly important, including for subsistence and commercial fisheries, coastal protection from storm surges and waves and reef-based tourism income, an important foreign exchange earner in many areas.



Box 1: The young at highest risk

Calcifying marine organisms appear to be particularly sensitive to ocean acidification during the larval and juvenile stages of their life cycles, in part because they form their internal skeletons out of amorphous calcite, which is more soluble than other forms of carbonate. The result is that the competitive advantage of these organisms will be significantly reduced, which will in turn alter the marine ecosystem. Observations thus far include:

- Reduced calcification rates (cold-water coral, blue mussels)
- Absence or reduction of shell size at pH 7.4 (oysters)
- Shell dissolution (clams)
- Absence in areas with a minimum pH of 7.4 (snails)
- Decrease in size (brittle stars)
- Abnormal development and morphology at pH 6.8 (pluteus larvae, e.g., sea urchins, brittle stars)
- Alteration of behaviour during critical life stages at pH 7.8 (clownfish)
- Mortality due to acidification of 0.2 units of pH(brittle stars)

The potential economic impact of ocean acidification is uncertain and will largely depend on how it affects the higher and most economically important levels of the food web. What is clear is that the goods and services provided by the ocean, upon which human populations depend, are changing as increasing CO_2 concentrations influence the physiology, development and survival of marine organisms.

Fisheries are major sources of employment, economic activity and nourishment. Tropical coral reefs are important habitats and feeding grounds for fish, producing 10–12 per cent of the fish caught in the tropics and 20–25 per cent of the fish caught by developing countries. The failure of coral communities to compete with algae communities that will not be similarly affected by ocean acidification will result in an ecological phase shift to a stable new ecosystem state dominated by less commercially valuable species. This could lead to a decrease in fishing revenues, with significant impacts for communities that depend on fishing for their income and livelihoods.

The total value of world fisheries production is presently around $150 billion per year. Approximately 50 per cent of all food fish come from aquaculture industries. Shellfish and crustacean aquaculture depends heavily on the capture in the wild of individuals that are kept for breeding purposes. Most aquaculture facilities are located in coastal areas that will probably experience ocean acidification. Reduced calcification and reproduction success in calcifying organisms will represent a significant loss of economic and livelihood opportunities from the aquaculture and commercial fisheries sectors, and are likely to affect developing countries that are heavily reliant on aquaculture for protein and revenue. While hard to predict, early estimates of the direct impact of ocean acidification on marine fisheries production are on the order of $10 billion per year.

Uncertainties

The magnitude of ocean acidification can be predicted with a high level of certainty based on complex but predictable marine carbonate chemistry reactions and cycles. The predicted consequences for marine plants and animals, food security and human health are profound, including disruption to fundamental biogeochemical processes, regulatory ocean cycles, marine food chains and production and ecosystem structure and function.

It should be said, however, that ocean acidification has only recently been recognized as a global threat, and its effects on global marine species, ecosystems and services is still poorly understood.

Ocean acidification research is still in its infancy. In particular, most understanding of the biological effects of ocean acidification has been derived from studies of individual organisms. Understanding of the short-term impacts of ocean acidification on different species of marine biota is building, and continuing scientific experimentation is facilitating a growing understanding of its wider ecosystem and long-term implications. There is also a need for more spatially distributed and temporally intensive studies of ocean pH dynamics and their underlying causal mechanisms and consequences, along with a focus on the adaptive capacities of marine organisms, which will be crucial to forecasting how organisms and ecosystems will respond as the world's oceans warm and acidify.

Looking ahead

Atmospheric CO_2 concentrations are predicted to increase throughout the twenty-first century and could more than double current concentrations (to 800 ppm) by 2100 if anthropogenic emissions continue along current trends. Increasing ocean acidification will follow directly (albeit with a time lag) the accelerating trend in world CO_2 emissions.

The corresponding decrease in surface water pH of between 0.14 and 0.4 units, to ~7.9, will be the equivalent of a 150 per cent increase in hydrogen ion concentrations and a 50 per cent decrease in carbonate ion concentrations from pre-industrial levels. The rate of change observed is at least 100 times more rapid than any experienced over the past 100,000 years. This is significant for biological systems and leaves little time for evolutionary adaptation to changes in ocean chemistry by marine organisms.

Since CO_2 is more soluble in colder waters than in warm, the surface waters of high-latitude oceans will be the first to become acidified. Given current CO_2 emission rates, it is predicted that the surface waters of the highly productive Arctic Ocean will become acidic by 2032 (with a decrease in pH of 0.45 units), making them corrosive to pteropods (shelled planktonic snails) and bivalves such as clams, which play a key role in Arctic marine food webs. By 2050, the same conditions will begin to be seen in the surface waters of the Southern Ocean and will spread to the entire Southern Ocean and subarctic North Pacific Ocean by 2100. Figure 3 shows the pre-industrial, present-day and projected future aragonite saturation state of the world's oceans.

Ocean acidification is irreversible in the short term. Substantial damage to ocean ecosystems can only be avoided through urgent and rapid reductions in global emissions of CO_2 by at least 50 per cent by 2050, and much more thereafter. Ocean acidification is an already observable and predictable consequence of increasing atmospheric CO_2 concentrations with biological impacts, and will need to be recognized and integrated into the global climate change debate.

1 Acidity and its opposite, alkalinity, are expressed in terms of "pH", an approximation of the concentration of certain hydrogen ions in a substance; pH is stated on a scale of 0–14, with 0 being the most acid, 14 being the most alkaline and 7 being neutral.

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