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OCEAN ACIDIFICATION

The increasing amount of carbon dioxide (CO_2) in the atmosphere is acidifying the oceans. The resulting changes to ecosystems and marine biodiversity may have negative impacts on fisheries and food security and reduce the coastal protection provided by coral reefs. This POSTnote outlines the science behind ocean acidification and summarises the threats to the marine environment. A global reduction of carbon emissions is the only certain way to minimise these risks.[1]

Background

Ocean acidification is a direct and measurable consequence of human emissions of CO_2. About 40% of CO_2 released into the atmosphere by human activities since the industrial revolution has been absorbed by the oceans. This CO_2 reacts with seawater causing the oceans to become more acidic. Acidity is measured in units of pH with lower pH values for more acidic solutions. A one unit decrease in pH equates to a ten-fold increase in acidity.

Past Changes to Atmospheric CO_2 and Ocean pH

Between 1750 and 2009, the atmospheric concentration of CO_2 increased from 280 to 387 parts per million (ppm). This has caused average surface ocean pH to decrease from 8.2 to 8.1. This is more acidic than the ocean has been for hundreds of millennia, and the rate of pH change is estimated to be 100 times faster than at any other time during this period[2].

Future Changes to Ocean pH

Surface ocean acidity can be calculated with a high degree of certainty for a given level of CO_2. If carbon emissions continue unchecked, surface ocean pH will decrease to between 7.6 and 7.8 by the year 2100.[3] Modelling studies have shown that the polar oceans will be first to experience the impacts of acidification and will become corrosive towards some shelled animals within decades.[3] Critically, even if CO_2 emissions are stopped entirely, it will take many thousands of years for pH levels to return to pre-industrial values.[1]

Issues

Some of the main issues and consequences of ocean acidification are summarised below:

- Ocean acidification threatens many marine species, habitats and ecosystems. Organisms with structures made from calcium carbonate ($CaCO_3$) are particularly vulnerable.
- Climate change and ocean acidification will occur simultaneously. The impacts of warming and acidification together may be more severe than their impacts in isolation.
- Acidification will reduce the capacity of the oceans to absorb CO_2 and increase the fraction of CO_2 emissions that remain in the atmosphere driving climate change. This impact may be amplified or lessened depending on the biological response of the ocean.
- Global negotiations on carbon emissions are currently focussed on the reductions required to avoid a global temperature increase of 2ºC. However, CO_2 levels that are designated ‘safe’ in terms of temperature may still have significant consequences due to ocean acidification.
- Potential social and economic impacts include reduced subsistence and commercial fishing catches and loss of valuable ecosystems such as coral reefs.

Impacts on Marine Life

The organisms most threatened are those which create shells, skeletons or structures from $CaCO_3$. Organisms that use aragonite (corals, mussels) or high-magnesium (high-Mg) calcite (sea urchins) will be especially sensitive to changes in ocean pH (see Box 1). Reduced capacity to calcify may make these organisms less competitive and more vulnerable to predators. Tropical and cold-water corals and shell-forming organisms in the polar oceans are thought to be especially vulnerable. Changes in ocean pH will also have other more subtle health impacts (such as changes in metabolism) on a variety of organisms.[4]

Acidification will negatively impact many marine species but it is probable that others will thrive due to reduced competition or increased availability of prey. One way in which the ecosystem response to ocean acidification has been estimated is by looking at a naturally acidified marine environment. A recent study examined a bay in the Gulf of Naples that is acidified by CO_2-releasing volcanic vents.[5] This study showed that there was a significant decrease in biodiversity, an absence of corals, and fewer calcifying organisms when pH was less than 7.8.

Box 1. Carbonate Chemistry Definitions

Calcium carbonate ($CaCO_3$) – a mineral that many marine organisms synthesize from seawater to create shells, skeletons, or other structures in a process called calcification. Acidification reduces the availability of carbonate ions (one of the chemical 'building blocks' of $CaCO_3$) making it more difficult to create shells.

Calcite – the form of $CaCO_3$ that is least sensitive to acidification.

Aragonite – a form of $CaCO_3$ that is especially sensitive to acidification..

High-Mg calcite – a form of calcite that has a sensitivity similar to aragonite.

Coral Ecosystems

It is thought that tropical and cold-water corals will be severely threatened by ocean acidification. Tropical coral reefs (Box 2) are large geological structures formed from the skeletons of living organisms and are some of the most biodiverse ecosystems on the planet. They provide food, protection from flooding caused by storms, and income from tourism to hundreds of millions of people. Tropical reefs also act as nursery and breeding grounds for commercial fisheries and are an essential part of the complex food-webs in the tropical coastal oceans.

Box 2. Case study 1: Tropical Coral Reefs

Tropical coral reefs are particularly threatened by climate change due to the combined impacts of ocean warming and acidification. Periods of unusual warmth cause 'coral mass bleaching' events which have killed a large number of corals since the 1980s. Bleaching events are expected to become more common in a warmer world.[6] In addition, experiments have shown that coral growth rates are decreased in more acidic seawater. At levels of CO_2 and pH predicted for the coming century, although tropical seawater will not become completely corrosive towards live corals, reef resilience is likely to become untenable as the delicate balance between accretion and erosion is disturbed. Reduced calcification by corals and other reef building calcifiers will result in weaker reef frameworks making them more susceptible to erosion from increased storm activity in a warmer climate.

Coral reefs are also threatened by sewage pollution, destructive fishing practices, and disease. Prevention of catastrophic loss of coral reefs will require rapid reductions in CO_2 emissions and careful management of these other pressures.

If CO_2 emissions continue at current rates, it is likely that all coral reefs will be severely affected by ocean acidification and ocean warming by 2050[1]. Even if CO_2 levels are stabilised at 450ppm, it is estimated that 92% of tropical reefs will be surrounded by seawater conditions that are unfavourable for coral growth.[7]

Cold-water corals (Box 3) are globally distributed and live in the deep waters at the margins of continental shelves. They are abundant to the west of the UK and elsewhere in the Atlantic. It is only in the last decade that their widespread distribution has been recognised due to improvements in deep-sea survey technology. Cold-water coral habitats might be as significant in the deep-ocean as tropical coral reefs are in the surface ocean.[8]

Box 3. Case Study 2: Cold-water Corals

Cold-water or deep-water corals are important habitat forming species and the reefs they form are centres for deep-ocean biodiversity. Deep-water reefs also act as spawning and nursery areas for many species. The most important reef forming cold-water corals are colonial 'stony corals' which build skeletons out of aragonite. Seawater becomes more corrosive to aragonite with depth. For this reason, cold-water corals and the reefs they build have a lower limit beyond which they cannot grow.

In experiments, cold-water corals show a reduction in calcification in more acidic seawater. In addition, as the oceans continue to absorb CO_2, the depth at which the ocean becomes corrosive to aragonite will move towards the ocean's surface. This impact will be felt most in areas of the ocean where CO_2-enriched surface waters sink to depth such as the North Atlantic. Cold-water corals are also very sensitive to changes in temperature and could also be affected by temperature-induced shifts in plankton productivity in the surface ocean.

Critically, cold-water corals are long lived and very slow to grow and slow to disperse. Development of reefs in the North Atlantic has taken many thousands of years. The rate of ocean acidification and warming may not give cold-water corals time to respond.

Primary Producers

Organisms at the very bottom of the food chain convert CO_2 into organic matter. This process is known as primary production and it is the ultimate source of energy for most life in the ocean. The majority of ocean primary production is performed by microscopic algae and some species may benefit from higher CO_2 levels. However, some primary producers also form $CaCO_3$ and may be affected by ocean acidification (Box 4). It is not certain how changes in the relative abundance of different primary producers will affect marine life.

Impacts on Calcifying Invertebrates

Many marine invertebrates—such as molluscs, crustaceans and echinoderms—use $CaCO_3$ to create shells or skeletons and are very important to coastal ecosystems, both economically and as part of coastal food-webs.

Molluscs

Experiments on bivalve molluscs, such as mussels, suggest that the growth rate of their hard shells will decrease with increasing CO_2. A recent study estimated that, by 2100, calcification will be reduced by 25% for mussels and 10% for oysters.[9] Other studies have shown that functions other than calcification (such as metabolism and immune responses) can also be affected by ocean acidification and that early life stages may be particularly sensitive.[4]

Pteropod molluscs are a type of swimming sea snail that form delicate shells. Their vulnerability is significant as they are an important food source for many marine species, especially in the polar regions. Their prevalence in the high-latitudes and their aragonite shells make them especially sensitive to ocean acidification. Experiments have shown that pteropods form weaker shells under high CO_2 conditions and can dissolve when exposed to seawater that is corrosive to aragonite.[3]

Box 4. Case Study 3: Coccolithophores

Coccolithophores are unicellular primary producers which form microscopic $CaCO_3$ (calcite) plates. These abundant and widespread algae can form large seasonal blooms and account for a large fraction of global $CaCO_3$ production. Most studies have shown a decrease in coccolithophore calcification at high levels of CO_2. However, some experiments have shown both increased and decreased coccolithophore calcification under elevated CO_2 conditions, even in the same species.[10,11] These conflicting results may be caused by differences between experiments or genetic differences between the strains used. The genetic variability of coccolithophores and their short lifetimes (days) may mean they have the capacity to adapt to higher levels of CO_2 in the future; however, the longest studies to date (150 generations) have shown no evidence of adaptation.[12]

Crustaceans

Many crustaceans, such as crabs and lobsters, have protective shells encrusted with $CaCO_3$. Acidification may harm larger crustaceans by reducing their capacity to reinforce their shells or indirectly through changes in prey populations. Experiments on crustaceans show that acidification can dissolve shells, reduce tolerance to temperature variability, and reduce the number of larvae that survive to adulthood.[4] Lower pH may also affect small planktonic crustaceans called copepods, one of the most abundant sources of protein in the oceans. Copepods are an important food source for many marine species, especially for the larval stages of many commercially valuable fish. Reduced pH might affect the ability of these organisms to form their shells. A study has also demonstrated that the hatching success of their larvae is reduced at extremely high levels of CO_2.

Echinoderms

Echinoderms, such as sea urchins and starfish, have skeletons and structures made from a soluble form of $CaCO_3$ (high-Mg calcite) which makes them especially sensitive to changes in ocean pH. Echinoderms play an important role in coastal and deep-ocean ecosystems, especially burrowing species which ventilate sediments. Experimental work shows that urchins exposed to low pH conditions can undergo shell dissolution, acidification of the blood, reduced fertilisation rates, reduced development speed, and reduced larval size.[4] One study has shown that at higher CO_2 levels, brittle stars will actually increase rates of calcification, but only at the cost of reduced muscle mass leading to impacts on physiological fitness.

Potential Impacts on UK Fisheries

Four of the ten most valuable marine species in the UK are calcifying shellfish or crustaceans (Table 1). These fisheries have grown substantially in the last decade. In 2007, nephrops (scampi) accounted for 24% of the total value of fish landed in the UK. The aquaculture (‘fish farming’) industry is another significant contributor to the UK economy. Aquaculture of shellfish—predominantly oysters and mussels—is annually worth £20 million in England and Wales (2006), £5 million in Scotland (2007) and more than £3.5 million in Northern Ireland. These statistics emphasise the importance of shellfish to the UK fishing fleet and highlight the potential for economic impacts as a result of ocean acidification.

Table 1 – Most Valuable UK Fisheries in 2007

Fish	Quantity (thousand tonnes)	Value (£ million)
Nephrops* (scampi)	44.1	126.4
Mackerel	100.3	67.1
Haddock	32.3	39.9
Scallops*	20.8	38.8
Crabs*	28.8	37.9
Monks or Anglers	13.8	34.1
Lobsters*	2.8	31.3
Cod	12.8	21.7
Soles	2.1	15.5
Whiting	13.1	11.7

Data source: *Sea Fisheries Statistics* 2007 (Marine and Fisheries Agency). *Calcifying species

The consequences of ocean acidification for nephrops are uncertain. These crustaceans inhabit burrows in sediments in which the ambient pH is lower than that of the surrounding seawater. For this reason, it is possible that nephrops will be better adapted to a lower pH environment than other crustaceans, but there is little evidence to support this assumption.

How fish will respond to changes in ocean pH and CO_2 levels is also poorly understood, although it is likely that they will be more resilient than shelled organisms. Available data suggest that larval and egg life-stages of fish will be the most sensitive. A recent study conducted by scientists from the Centre for Environment, Fisheries and Aquaculture Science (CEFAS, an executive agency of Defra) showed that larval survival was poorer when pH was reduced to predicted future values, and that egg fertilisation was also impaired.

Many fish also depend on calcifying organisms (such as crustaceans, echinoderms, molluscs and calcifying plankton) as food sources. Records show that both juvenile and adult fish have adapted their diets in the past. However, many species still have a preferred range of prey and it is not clear what would happen to fish such as haddock (which feed nearly exclusively on echinoderms) if calcifying organisms were affected by ocean acidification.

Ocean Acidification Research

Ocean acidification research is still in its infancy and, to date, most experiments studying the impacts on marine life have focused on the response of individual species under laboratory conditions. There is no straightforward way to scale up laboratory results to make global or ecosystem-wide predictions. Current experimental work is also focused on those species which are tolerant enough to be kept under laboratory conditions, not those which have the most relevance for society.

Research Programmes

There are currently three major ocean acidification research programmes in Europe. The European Project on Ocean Acidification (EPOCA) is funded by the EU (€6.5

million) and has several partner institutions from the UK. The Biological Impacts on Ocean Acidification (BIOACID) programme is funded by the German government (€9.3 million). The five year UK Ocean Acidification Research Programme (£12 million) begins in 2009 and is jointly funded by the Natural Environment Research Council (NERC), the Department for Environment, Food and Rural Affairs (Defra) and the Department of Energy and Climate Change (Decc). To make best use of available funding, international collaboration between scientists and institutions is being strongly encouraged by all three programmes. In the USA, the Federal Ocean Acidification Research and Monitoring (FOARAM) Act has authorised appropriations for ocean acidification research and monitoring worth $96 million over 4 years, starting in 2009.

Research Priorities

In October 2008, scientists from around the world gathered in Monaco to discuss the impacts of ocean acidification. One of the outcomes of this meeting was a report outlining the priorities for future research.[12] These include the following:

- the development of experiments and models to evaluate ecosystem-wide responses to acidification;
- longer-term studies to estimate the potential for adaptation or evolution of different species;
- the establishment of a network of ocean CO_2 and pH monitoring stations to identify natural variability and long-term trends in ocean pH.

This last priority is important as little is currently known about the variability of pH in most of the oceans, especially in coastal areas. This type of ocean monitoring is expensive but the information is essential for predicting which areas will be most vulnerable and for assessing the effectiveness of mitigation efforts.

Policy and Mitigation

There is currently no UK or international legislation that directly addresses the problem of ocean acidification. For this reason, the science academies of the world are currently calling on world leaders to acknowledge the combined threat of ocean acidification and climate change when negotiating carbon emissions reductions for 2012 and beyond[1]. On June 1st 2009, the Interacademy Panel on International Issues (IAP)—a global network of 70 science academies including the UK's The Royal Society—issued a statement reading, "Even with stabilisation of atmospheric CO_2 at 450 ppm, ocean acidification will have profound impacts on marine systems. Large and rapid reductions of global CO_2 emissions are needed globally by at least 50% by 2050."

The forthcoming EU Marine Strategy Framework Directive (MSFD) dictates that all member states are required to achieve "good environmental status" in the marine environment by 2020. To this end, the UK government is committed to delivering "clean, safe, healthy, productive and biologically diverse oceans and seas"[13] through the establishment of a "strong, ecologically coherent and well managed network of Marine Protected Areas (MPAs)"[14] by 2012 as part of the Marine and Coastal Access Bill. MPAs are designed to protect the marine environment from the impacts of unsustainable fishing, pollution and other destructive practices and may help to maximise the resilience of ecosystems by reducing the impacts of other human pressures. The MSFD also requires that "permanent alteration of hydrographical conditions does not adversely affect marine ecosystems". The required monitoring programmes specifically mention pH and dissolved CO_2 as 'characteristics' to be monitored by EU member states.

Geo-engineering

The concept of geo-engineering involves large-scale engineering to counteract the impacts of climate change, either by removing CO_2 from the atmosphere or by increasing the amount of energy from the sun that is reflected back into space (see POSTnote 327). However, any geo-engineering methods that do not reduce levels of CO_2 in the atmosphere will not prevent ocean acidification and the risks and consequences of these geo-engineering methods are uncertain. The addition of alkaline minerals to the ocean has been proposed as a geo-engineering solution to acidification. However, this method would be effective only in very small, restricted areas of the coast. On a global scale, this option would be economically prohibitive and come with an unknown environmental cost.[2]

Summary

- Human emissions of carbon dioxide (CO_2) are causing the oceans to become more acidic.
- Ocean acidification threatens many marine ecosystems, especially tropical and cold-water corals and shell forming organisms in the polar oceans.
- Social and economic consequences will disproportionately affect the poorest parts of the world, especially those which rely on income and coastal protection from coral reefs.
- The vulnerability of shellfish may have unforeseen consequences for fishing and aquaculture industries.
- The only practical way to minimise the impacts of ocean acidification is to reduce emissions of CO_2.

Endnotes

1 Interacademy Panel on International Issues, *IAP Statement on Ocean Acidification*, 2009.
2 Royal Society Policy Document, *Ocean acidification due to increasing atmospheric carbon dioxide*, 2005.
3 Orr *et al.*, *Nature* 437, 2005.
4 Fabry *et al.*, *ICES Journal of Marine Science* 65, 2008.
5 Hall-Spencer *et al.*, *Nature* 454, 2008.
6 Hoegh-Guldberg *et al.*, *Science* 318, 2007.
7 Cao and Caldeira, *Geophys. Res. Lett.* 35, 2008.
8 Roberts *et al.*, *Science* 312, 2006.
9 Gazeau *et al.*, *Geophys. Res. Let* 34, 2007.
10 Riebesell *et al.*, *Nature* 407, 2000.
11 Iglesias-Rodriguez *et al.*, *Science* 320, 2008.
12 Orr *et al.*, *http://ioc3.unesco.org/oanet/HighCO2World.html,* 2009.
13 Defra, *Safeguarding Our Seas*, 2002.
14 Defra, *Delivering Marine Conservation Zones and European Marine Sites*, 2009.

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