CLIMATE CHANGE'S FAMOUS COUSIN

Ocean acidification has transitioned from a little-known phenomenon to a buzzword within a span of five years. The concomitant explosion of research on this topic has provided many general insights into its effects. But as **Sarah Cooley** reminds us, many of the specifics regarding its consequences for humans and ecosystems await elaboration.

Ocean acidification refers to the progressive decrease in ocean pH and carbonate-ion (CO_3^{2-}) concentration as the oceans take up anthropogenic carbon dioxide from the atmosphere. The term appears in the media under many colourful aliases including "the other carbon dioxide problem" and "climate change's evil twin." The speed at which this phenomenon has gained nicknames reflects the exponential rise in research over the past five years.

A milestone in our awareness of this issue was the First Symposium on the Ocean in a High-CO_2 World, which was held in Paris in 2004. Since the first report of acidification's harmful effects on pteropods – creatures such as sea snails – appeared in 2005, the number of published scientific articles on the topic has approximately doubled each year from 2006-2009 (red bars, Figure 1). The rate for the first half of 2010 suggests that the trend may indeed continue. Compared with the steadily increasing number of papers on climate change mentioning the ocean (blue bars, Figure 1) over two decades, the number of ocean-acidification research papers has simply exploded.

Anthropogenic carbon dioxide is profoundly affecting marine chemistry.

The message from this research is clear: anthropogenic carbon dioxide is profoundly affecting marine chemistry and many marine organisms are likely to be affected. If ocean acidification alters ecosystem services such as shellfish harvests, humans are likely to feel the sting. It is this potential to cause economic (and thus perhaps socio-political) disruption that has led policymakers to take a special interest in the process. Along with research articles, summaries for policymakers are also proliferating. Nevertheless, gaps in understanding remain and it is still too early to develop comprehensive management plans that account explicitly for the effects of acidification. Such plans might eventually become necessary components of strategies to adapt to global change, which is why broad research to integrate and extend our understanding of acidification is essential.

A multifarious problem

Until atmospheric carbon dioxide levels began rising rapidly due to human industrial activities and land-use changes in the late nineteenth century, air-sea carbon dioxide exchange remained in a state of balance. Rising atmospheric carbon dioxide in the past two centuries, however, has disturbed the equilibrium: to restore it, surface seawater is now taking up more of this gas. Dissolved carbon dioxide reacts with water to generate carbonic acid, and some of the carbon dioxide also reacts with carbonate ions – used by organisms to make their shells – in seawater to form bicarbonate ions (See 'Basics of acidification' on the following page). In geologic terms, the ocean's uptake of anthropogenic carbon dioxide is faster than the blink of an eye. Before we used fossil fuels, compensatory changes in rock weathering or carbonate burial occurred over millennia. Marine life adapted to changing ocean chemistry over thousands or millions of generations. But we are now emitting carbon dioxide much faster than geologic controls can mop it up, so the ocean's pH and carbonate-ion concentration have decreased measurably since the start of the industrial age.

We know from studies conducted over the past few years that ocean acidification can have several effects. Many studies show that ocean acidification robs marine organisms such as some molluscs and corals of the raw material they need to build calcified shells and skeletons. Rising carbon dioxide levels increase photosynthesis in some phytoplankton and enhance nitrogen fixation in others. This could alter global biogeochemical cycling of carbon and nitrogen, and it could influence the marine food web by changing the types of phytoplankton available for predators. In some larger organisms, the effects of acidification depend on metabolic rate. More active animals can more easily regulate physiological processes over the short periods that have been studied so far, whereas those with low metabolic rates may be more susceptible to acidosis, metabolic depression

Basics of acidification

Dissolved carbon dioxide (CO_2) reacts with water to generate carbonic acid (H_2CO_3), which dissociates to release hydrogen ions (H^+), bicarbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-}):

$$CO_2 + H_2O \leftrightarrows H_2CO_3 \leftrightarrows H^+ + HCO_3^- \leftrightarrows 2H^+ + CO_3^{2-}.$$

Some of the carbon dioxide also reacts with existing carbonate ions, but this reaction does not change the pH:

$$CO_2 + H_2O + CO_3^{2-} \leftrightarrows 2HCO_3^-.$$

The net effect of these reactions is to lower pH by releasing hydrogen ions and reduce the supply of carbonate ions in seawater.

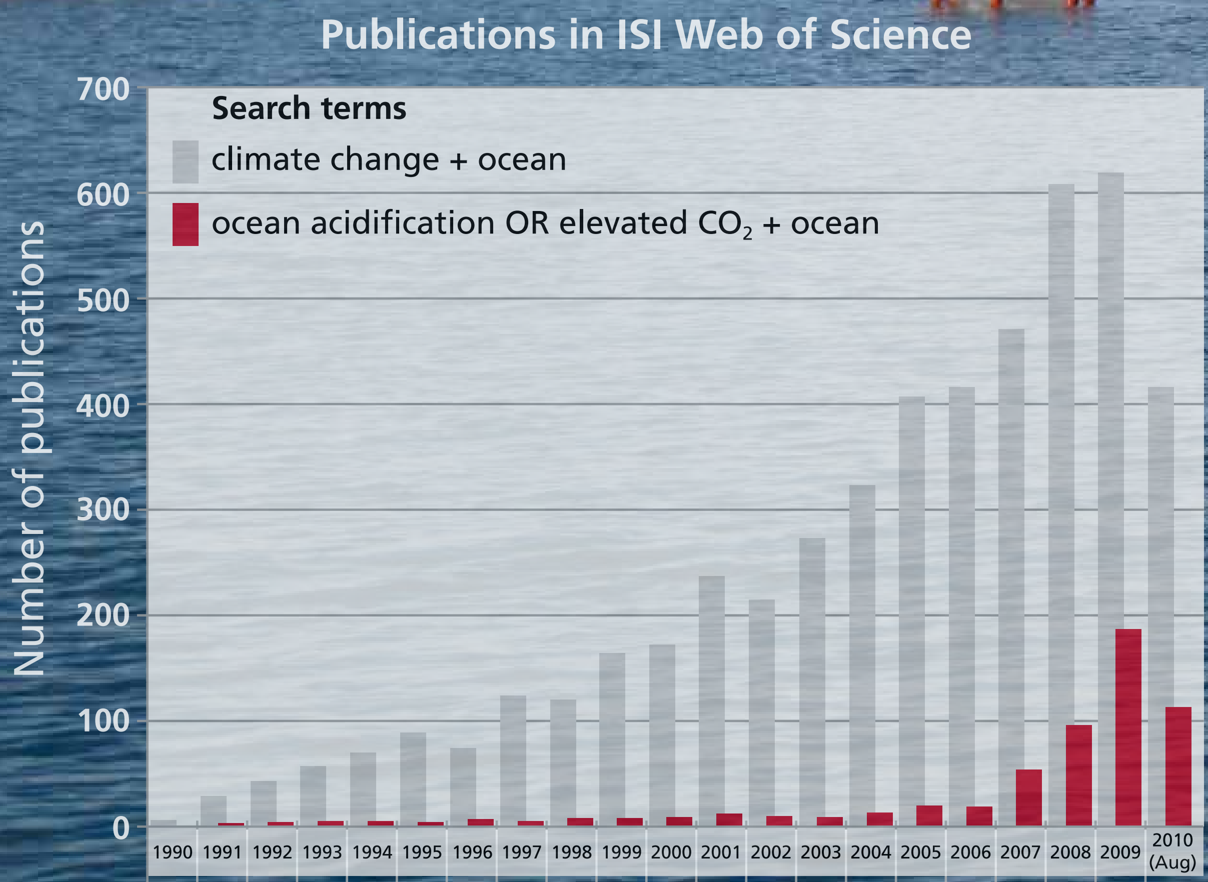

Photo: Ulf Riebesell; IFM-GEOMAR

or reduced respiratory efficiency. Acidification also affects marine organisms in unusual ways, for example, by slightly increasing sound transmission and making very quiet areas of the ocean a bit noisier. Such differing and subtle responses make forecasting consequences difficult.

In addition to affecting single organisms, ocean acidification could also alter interactions among them, which could alter whole populations. For example, carbon-dioxide-loving sea grasses could overtake damaged coral reefs and provide food and habitat for a different set of species. Food-web interactions would then convey and magnify these changes through the ecosystem. After regime shifts like this in which a profound ecosystem-wide transition occurs, diversity is likely to decline. Ecosystems with decreased biodiversity because of climate change or disease have become less resilient and suffer more from multiple stressors. Early data suggests that population-level effects seem poised to alter ecosystems profoundly by favouring a different array of organisms (Box 1).

Ocean acidification occurs in combination with other stressors such as climate change and human activities. Anthropogenic climate change increases temperatures and alters freshwater cycling, both of which change the layering of oceans. This in turn modifies nutrient cycling and insolation, affecting phytoplankton. Human activities alter coastal zones by diverting rivers or increasing erosion. Rising temperatures and melting sea ice may encourage new ocean-acidification-tolerant predators to invade high latitudes, where ocean-acidification-sensitive organisms suffer from direct effects of chemical change as well as from temperature change, habitat shifts and overfishing.

We now know quite a bit about ocean acidification. However, new research results often raise more questions. And placing results in context or applying them to other times and places remains a challenge. Deeply integrated efforts are required to advance our knowledge about ocean acidification henceforth (see the research priorities outlined recently by the United States National Research Council).

Box 1. Ecosystem-level effects

In the Mediterranean Sea, near Ischia (Italy), Jason Hall-Spencer and his colleagues studied ecosystems surrounding natural volcanic carbon dioxide (CO_2) vents to examine what might happen in future high-CO_2 oceans. The researchers used distance from these vents as a proxy for time: compared with seawater, locations moderately close to the vent had slightly lower pH values and slightly higher concentrations of carbon dioxide. Locations very close to the vent, though, had much lower pH values and much higher carbon-dioxide concentrations. The researchers found that the permanent concentration gradient governed the entire ecosystem structure in this environment. Non-calcareous algae replaced calcareous algae, sea urchins, limpets and barnacles as carbon dioxide levels rose and pH dropped near the vents. Moreover, they did not observe any juvenile calcifiers near the vents and noted that adult calcifiers appeared damaged.

Hall-Spencer J M *et al.* (2008) *Nature* 454: 96-99, doi:10.1038/nature07051.

Ocean acidification occurs in combination with other stressors such as climate change.

A large unknown is how ocean acidification will affect coastal zones. In the global ocean basins, open-ocean pH and carbonate-ion variability are low and trends are apparent. But what happens near coastlines, where seawater chemistry already varies greatly due to biological activity, runoff and physical circulation? Here, small progressive changes from ocean acidification are not easy to detect among all the other strong natural and anthropogenic signals. Positive or negative feedbacks may occur from nutrient cycling, weathering, upwelling and acid rain. Coastal regions' responses to ocean acidification will depend on all such factors.

Another issue awaiting resolution is to what extent the effects of ocean acidification will vary among species. For example, numerous laboratory experiments have shown that the net calcification rates for many organisms such as temperate corals and oysters decrease in response to lower pH or increased CO_2, and shells of some organisms even dissolve. Other organisms with calcified shells, such as crustaceans, seem not to behave the same way (Ries *et al*. 2009). To add to the complexity, responses sometimes vary among species within the same genus (Miller *et al*. 2009). To know why some species, but not others, are susceptible, we will need to understand the physiological mechanisms behind varying responses. Are organisms more sensitive during certain life stages? Does early damage affect individuals throughout their lives, or are some individuals simply always more susceptible?

The outlook

To take our understanding of ocean acidification to the next level, we need to determine how ecosystems, and not just individual organisms, will respond to acidification. Some ecosystem responses to perturbations may be similar regardless of cause; for example, coral "flattening" due to climate change – where reduced architectural complexity decreases diversity and species make-up – may also result from other stressors like ocean acidification (Alvarez-Filip 2009). Changes in species abundance and biodiversity often follow ecosystem perturbations, so understanding general or

Box 2. Fisheries under pressure

If mollusc harvests in the US decrease due to ocean acidification, direct losses could amount to several billion dollars by the middle of the century, a recent study suggests. Indirect losses, which would result from the impact on allied businesses (wholesale and retail sales, transportation), would therefore also affect regions with marine-dependent economies. In this situation, fishing communities like New Bedford in Massachusetts – already under economic duress – could lose over a billion dollars by the middle of the century. And jobs will inevitably be lost as well. Commercial fisheries, including processing and sales, contribute tens of billions of dollars to the US Gross National Product (GNP) and generate tens of thousands of jobs. Recreational fishing and associated spending also substantially contributes to the GNP and generates hundreds of thousands of jobs. Because of the many unknowns regarding how ocean acidification could affect ecosystem services, these types of economic impact analyses are preliminary and are accompanied by large uncertainties. But such analyses are an important first step towards guiding policies and encouraging interventions. They are also a call for continued research on ocean acidification at local, regional and global scales.

Cooley S R and Doney S C (2009) *Environmental Research Letters* 4, doi:10.1088/1748-9326/4/2/024007.

specific responses to disturbance is vital to understanding and predicting ecosystem change due to ocean acidification.

We have learned and continue to learn a lot from laboratory experiments but we now also need experiments in natural environments involving real-world conditions. One way to do this is to employ mesocosms – large-volume enclosures, essentially plastic bags – suspended in the sea. In these bags, researchers vary carbon dioxide levels and observe the response of organisms within. The European Project on Ocean Acidification (EPOCA), for example, brought together researchers from around the world to do this type of study in the Arctic Ocean in June and July this year. Studies like this will help us figure out how natural systems respond to sudden changes, and they may indicate the limits of ecosystems' resilience to change.

Finally, given the potentially large economic and social implications of ocean acidification (Box 2), we need more integrated research that can inform development of management strategies. Policymakers at all levels and marine resource users are becoming aware of ocean acidification and are beginning to seek information that can support decisions. Various countries are developing multidisciplinary ocean acidification research programmes. Activities as focused as topical workshops (e.g., the November workshop of the Monaco Environment and Economics group) or as broad as international working groups are under way to link oceanographic issues to socioeconomics (e.g., the IMBER human dimensions working group now being developed). Moreover, the IPCC will address the oceanographic and human dimensions of ocean acidification in its fifth assessment report. The organisational efforts now under way aim to bring together researchers and users in ways that incorporate everyone's perspectives, approaches and needs.

Relating ocean acidification to other decision-relevant issues like climate change will contribute to more universal management plans. For example, since ocean acidification was widely recognised, proposed climate-change mitigation strategies now usually include reducing atmospheric carbon dioxide to combat both climate change and acidification. Nevertheless, it is clear that a great deal of research is still needed to answer the many unknowns specific to ocean acidification and to plan for the future. ▮

We need more integrated research that can inform the development of management strategies.

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IGBP PARTICIPATION

In 2009, IGBP's marine projects IMBER and SOLAS launched a working group to coordinate international research on ocean acidification and to conduct regular syntheses. The group has at its core the European Project on Ocean Acidification EPOCA, and hopes to facilitate the involvement of the ocean acidification community in the IPCC assessments.