UK Ocean Acidification programme synopsis

Ocean acidification impacts in the upper ocean
How will ocean acidification affect plankton and their role in marine processes?

Ocean acidification changes seawater chemistry in ways that are mostly well understood. What is much less known is the impact that those chemical changes will have on marine organisms and ecosystems, particularly plankton (small plants, animals and microbes living in the water column) that play a crucial role in recycling nutrients and driving the exchange of many gases with the atmosphere, with potential feedback influences on global climate.

In most ocean acidification studies on plankton to date, single species have been subjected to elevated CO₂ (and the associated lower pH/increased acidity) in tanks or flasks. An advantage of these laboratory experiments is control: everything is kept constant except for the changes to CO₂ and pH, so the cause-response linkage is clear.

However, there are limitations to such studies. There are many thousands of planktonic species with different physiologies and behaviours, in very many taxonomic groups: it is impractical for them all to be individually cultured and studied. Furthermore, they do not always respond in the same way in nature as they do in the artificial conditions of a laboratory.

This synopsis is primarily based on work carried out by the UKOA consortium project Ocean acidification impacts on sea surface biology, biogeochemistry and climate. The consortium was led by Toby Tyrrell, University of Southampton, in partnership with the British Antarctic Survey, the Marine Biological Association, the National Oceanography Centre (Southampton and Liverpool), Plymouth Marine Laboratory, the Scottish Association for Marine Science, the Sir Alister Hardy Foundation for Ocean Science, University College London, the University of East Anglia and the universities of Essex and Oxford. The main focus of the work was at-sea observations and experiments in a wide range of localities (around the British Isles, the Arctic Ocean and the Southern Ocean), taking full account of natural environmental variability and complexity.

Specific aims of the consortium were:

- To determine the impact of ocean acidification on planktonic organisms, in terms of physiological impacts, morphology, population abundances and community composition
- To quantify the effects of ocean acidification on biogeochemical processes affecting the ocean carbon cycle, both directly and indirectly
- To quantify the impacts of ocean acidification on the air-sea flux of climatically active gases.
Key findings:

By undertaking experiments and making observations at a wide range of sites, an improved understanding has been gained of how ocean acidification affects planktonic organisms living in their natural environment.

- The shells of pteropods (sea butterflies) are already being damaged by increased CO$_2$, potentially affecting their behaviour and survival. The future loss of pteropods from polar seas would cause major changes to their food webs.

- Ocean acidification may decrease the production of nitrous oxide (N$_2$O), a greenhouse gas, whilst increasing production of dimethyl sulphide (DMS). Both effects could slow global warming, but need to be confirmed.

- The rate of shell growth of coccolithophores (calcifying phytoplankton) is slowed under experimentally-increased CO$_2$. However, present day natural variability in seawater pH and carbonate saturation state is not an overriding control on coccolithophore calcification or abundance.

- Small phytoplankton may be less successful, with slower growth, in a high CO$_2$ world.

- Impacts of carbonate chemistry changes in the upper ocean will not be equal everywhere, but will depend on site-specific environmental conditions, particularly in shelf seas and coastal waters.

Outputs:


Hopkins FE & Archer SD (2014) Consistent increase in dimethyl sulfide (DMS) in response to high CO$_2$ in five shipboard bioassays from contrasting NW European waters. Biogeosciences 11, 4925-4940


Richier S, Achterberg EP, Dumousseaud C et al. (2014) Phytoplankton responses and associated carbon cycling during shipboard carbonate chemistry manipulation experiments conducted around Northwest European Shelf Seas. Biogeosciences 11, 4733-4752


The ‘sea surface’ consortium has been active in outreach products including its own website, where cruise blogs, reports and educational materials can be accessed: http://www.surfaceoa.org.uk. Cruise and experimental data are lodged with the British Oceanographic Data Centre.

From a full list of publications arising from this component of the UKOA programme, see separate hard-copy document or online at www.oceanacidification.org.uk
Sea butterflies in trouble

Pteropods, or sea butterflies, are small planktonic snails that are regionally important in foodwebs and ecosystems, as food for seabirds, fish and whales; they may also have a significant role in global biogeochemistry. Pteropods are vulnerable to ocean acidification (particularly in colder waters) since their shells dissolve when carbonate saturation states are low.

UKOA researchers investigated the sensitivity of the Southern Ocean pteropod *Limacina helicina antarctica* to water chemistry conditions through experiments on board ship at a range of different acidification levels. Furthermore, they also found that, at some localities, free-living pteropods were already showing the same signs of shell erosion as occurred in the experiments. Calculations showed that this was as a result of the extra CO$_2$ that has been added to the atmosphere by human activities, altering ocean chemistry on a global basis. In particular, the extra CO$_2$ has caused changes to mid-depth water around Antarctica, that naturally has higher CO$_2$ (and lower pH) than at the sea surface. Although UKOA field observations showed that some shell repair by pteropods is currently possible, repair may not be able to keep pace with corrosion under near-future atmospheric CO$_2$ conditions, when both Southern Ocean and Arctic waters are projected to become corrosive for unprotected carbonate structures at all water depths, at all times of year. The loss of polar pteropods could have major ecological implications.
How are micro-plankton affected? A novel bioassay approach

Experimental manipulations on single species (such as pteropods, above) provide valuable insights, but are less instructive for micro-plankton communities. UKOA scientists devised and implemented short-term (2-8 days) bioassay studies to investigate the effects of carbonate chemistry changes on natural communities of phytoplankton, micro-zooplankton and bacteria, at realistic (natural) nutrient levels.

These studies were carried out on RRS Discovery around the British Isles, and on RRS James Clark Ross in the Arctic Ocean and Southern Ocean. Although the duration of experiments was restricted, it allowed more experiments to be carried out, and demonstrated the repeatability of results at a single site. A consistent pattern was observed: small-celled phytoplankton were suppressed by decreased pH/increased CO$_2$ but only under particular environmental conditions (only at sites where the water was warmer, probably because of how temperature affects the carbon chemistry). Results for other processes, presented below, were more variable, indicating that short-term community responses can be influenced by differences in initial community species composition, their size structure, and environmental factors.

**Coastal complexity**

Complementary observational studies showed the complexity of natural carbonate chemistry variability, particularly for near-coastal waters where river flows can match or dominate biological effects. Even in deeper water, water column mixing and associated temperature effects can have very strong influences. Such findings show that projection of future ocean acidification impacts in shelf seas (and also their future monitoring) must also consider the many factors that can affect pH and other carbonate chemistry parameters, whilst also taking account of seasonal changes.
Ocean acidification effects on biogases: negative feedback on climate change?

Marine phytoplankton and bacteria in the upper ocean drive major exchanges – both uptake and release – of a range of climatically-active gases between ocean and atmosphere. During conditions of climatic stability, there will be an overall balance of these different effects. However, when environmental conditions change (for example, increased atmospheric CO₂), feedbacks can occur that might be either positive or negative, reinforcing or counteracting the original driver of change.

One marine biogas of high scientific interest is dimethyl sulphide (DMS), the greatest natural source of sulphur to the atmosphere. DMS has a potentially-important cooling role, by assisting cloud formation, and is derived from the bacterial breakdown of dimethyl sulfoniopropionate (DMSP), produced by a variety of phytoplankton species. In shipboard experiments, UKOA researchers explored the short-term response of DMS and DMSP to experimental ocean acidification conditions. Using seawater samples from North West European seas, that encompassed a range of biological and biogeochemical conditions, they consistently found marked increases in DMS, and decreases in DMSP, in response to ocean acidification. If this short-term response is a valid simulation of future changes in a high CO₂ world, then increased DMS release could produce a negative feedback on global warming. However, opposite effects were found on other cruises carried out by the consortium, and in marine mesocosms (enclosed volumes of seawater, under near-natural conditions). The reasons for these differences are not fully understood, and need to be resolved.

Nitrous oxide (N₂O) is a powerful greenhouse gas produced by marine bacteria and archaea, particularly under low oxygen conditions. In the atmosphere, it is responsible for around 300 times more global warming per molecule than CO₂. UKOA shipboard incubations to determine the short-term impacts of ocean acidification on N₂O production were initially carried out on near-surface seawater samples: no effects were found. However, tests on seawater samples from 50-100 m water depth, where N₂O is naturally higher, found clear evidence that decreased pH inhibited the production of this gas. Thus the global ocean might change from a weak source to a weak sink for N₂O, providing negative feedback for global warming.

Additional studies are needed to quantify the scale and significance of such effects under different climate change scenarios, with particular interest in the potential interactions between acidification, N₂O production, de-oxygenation and increased temperature.

Locations of sampling in NW European shelf waters Satellite image courtesy NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS)
Coccolithophores are small, single-celled floating algae (phytoplankton) that have an exterior covering of calcium carbonate plates or liths. They can be very abundant in the ocean, forming blooms that make the water a milky-blue—a feature that can be seen from space. Early ocean acidification studies indicated that one of the commonest species, *Emiliania huxleyi* (included in the UKOA logo), might be particularly sensitive to high CO$_2$—with potential for secondary impacts that could not only affect other marine life but also the ocean carbon cycle, at a global scale.

Further laboratory experiments on this species, and other coccolithophores, showed that their responses to carbonate chemistry changes were complex and could be highly variable. UKOA research has investigated these issues using a field-based approach: a summary is given below of experiments on natural communities and related observational studies, the latter linking spatial and temporal environmental variability to species’ responses.

**Experimental studies**

In the UKOA experiments carried out at sea during the ‘round Britain’ research cruise, coccolithophores (with other micro-plankton) were subjected to a range of future pH/CO$_2$ scenarios. Individual organisms were subsequently examined using a scanning electron microscope. No nutrients were added to the experimental samples, to simulate the natural conditions that might occur during a period of population growth and nutrient depletion. In the control samples, the number of coccolithophore cells increased up to 10-fold during the four day experiment. In the acidified samples (at 500ppm, 750 ppm and 1000 ppm CO$_2$), slower population growth occurred at most, but not all, sites. One, relatively rare, species *Braarudosphaera bigelovii* seemed particularly sensitive to the carbonate chemistry treatments, possibly because it forms calcified plates at its cell surface, rather than internally, as is the case for *E. huxleyi*. End-of-experiment measurements of *E. huxleyi* cell size and plate features, including degree of calcification, did not show any significant treatment effects. These results reinforce an emerging consensus that the net effect of ocean acidification on most coccolithophores, whilst detrimental, may not be as severe as initially supposed.

**Observational studies**

Considerable spatial variability can occur in carbonate chemistry conditions: during the summer ‘round Britain’ UKOA research cruise in 2011, near-surface pH values varied between 7.90 to 8.15, and calcite saturation values from 3.5 to 4.5. However, community calcite production (primarily by coccolithophores) seemed unrelated to these changes; instead light availability was the most important factor, presumably through effects on photosynthesis.

During the winter, seasonally-driven changes further reduce pH and saturation rate, and light levels are lower. One or both of these factors might therefore be expected to reduce coccolithophore calcification. A large scale observational study tested such ideas, by collecting *E. huxleyi* samples monthly for 2 years, along a 1000km transect in the Bay of Biscay. The results of the study contradicted expectations: in winter the most abundant strain or morphotype (visually distinct, but considered to be the same species) of *E. huxleyi* was the highly calcified type.

Genetic factors will most likely be involved in the future response of coccolithophores to ocean acidification. *E. huxleyi* has large population sizes and rapid generation times, with high genetic variation. Such variation could result in genetic adaptation through selection of individuals that evolve resilience to its effects. However, genetic studies carried out on the UKOA research cruises showed that, contrary to current understanding, asexual rather than sexual reproduction predominated during blooms. The different strains of *E. huxleyi* may therefore actually be different species—and that might help explain the observed variability in both laboratory and field results.

The possibility that coccolithophores as a group might already be declining in abundance as a consequence of ocean acidification was investigated through analysis of North Atlantic samples collected by the Continuous plankton recorder for the period 1960 - 2009. Neither coccolithophores, pteropods nor foraminifera (another group of calcified zooplankton) showed significant temporal trends to indicate that such changes were already underway, although impacts of changing temperature were apparent in those datasets. Genetic changes may, however, have taken place over that period, and may continue to do so in the future. The fate of coccolithophores in a high CO$_2$ world is not as simple as once thought.
What is ocean acidification?

The global ocean currently absorbs more than a quarter of the CO₂ produced by burning fossil fuel and other human activities, slowing the rate of climate change. Global warming would therefore be far worse if it were not for the ocean. However, there is a cost: when CO₂ dissolves in seawater it forms carbonic acid, decreasing the pH and causing other chemical changes. These processes are known as ocean acidification.

Ocean acidification is a relatively new field of research, with the overwhelming majority of studies carried out over the last decade. While the topic is attracting increasing attention among policy makers, international leaders and the media, there is still much to be understood about the fundamental biogeochemical, physiological and ecological processes; interactions with other stressors (notably temperature change) and the consequences of ocean acidification for society. UK scientists are at the forefront of these research areas, working in partnership with many international colleagues.

What is the UK Ocean Acidification research programme?

Widespread concern about ocean acidification emerged after the Royal Society report Ocean acidification due to increasing atmospheric carbon dioxide in 2005. A range of research initiatives were subsequently developed at both the national and international level.

The £12m, five year UK Ocean Acidification research programme (UKOA) was the UK’s response, starting in 2010 and 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).

The overall aims of UKOA were to increase understanding of processes, reduce uncertainties in predicting impacts and improve policy advice. Scientific studies have included observations and surveys; impacts on upper-ocean biogeochemistry; responses by seafloor organisms; effects on exploited species, foodwebs and human society; ocean acidification in the geological past; and regional and global modelling. In addition to national policy liaison, UKOA has made significant contributions to the work of the Intergovernmental Panel on Climate Change (IPCC), the UN Framework Convention on Climate Change (UNFCCC), the UN Convention on Biological Diversity (CBD), the UN Sustainable Development Goals (SDGs) and many other governmental and non-governmental initiatives and activities.