



UK Ocean Acidification
Research Programme

UK Ocean Acidification programme synopsis

Seabed organisms and ecosystems



How ocean acidification might affect life on the seafloor

The benthic habitats and organisms of the seafloor play a crucial role in maintaining a healthy, productive and biologically diverse ocean, particularly in near-coastal areas. Around 40% of the world's population lives within 100 km of the coast, and many of those depend on accessible marine ecosystems for food, economic prosperity and well-being.

Coastal benthic habitats are, however, already at risk from over-exploitation, pollution and climate change: the scientific need is to determine what additional risks there might be from ocean acidification. In particular, which organisms are likely to be tolerant to high CO₂ and which are vulnerable; whether physiological tolerance might be due to acclimatization (plasticity) or genetic adaptation; and how the interactions between individuals (which determine ecosystem structure and function) will be affected.



Caption

UKOA seabed studies were mostly carried out by a consortium project **Impacts of ocean acidification on key benthic ecosystems, communities, habitats, species and life cycles**, led by Steve Widdicombe at Plymouth Marine Laboratory. Formal partners were at Cefas, the Marine Biological Association, the Scottish Association for Marine Science, and the universities of Aberdeen, Bangor, Heriot-Watt, Plymouth, Southampton and St Andrews. The overarching aim was to quantify and predict the impact of ocean acidification on biodiversity and ecosystem functioning in three key UK coastal habitats; soft sediments, calcareous biogenic habitats (such as cold water coral reefs and maerl beds), and the rocky intertidal. Three main approaches were used: laboratory experiments, many of relatively long duration and also investigating warming impacts; research cruises, to study cold water corals off North West Scotland; and research at CO₂ vents in the Mediterranean, where marine organisms and ecosystems have naturally been exposed to longterm ocean acidification at a local scale.



Caption

Specific objectives of the consortium were to:

- Quantify the impact of ocean acidification and warming on the health and activity of key benthic organisms; on the biogeochemistry of marine benthic habitats; and on marine benthic microbial communities
- Assess the potential for organism adaptation to ocean acidification and warming
- Predict the impact of future CO₂ on the population dynamics of benthic marine organisms, and on the biodiversity and functioning of coastal habitats.

Key findings:

Many seafloor organisms do have physiological processes for tolerating high CO₂. However, use of such mechanisms over extended periods increases energetic costs, potentially reducing growth and reproduction. When small environmental changes causing incremental harm continue over generations, populations are likely to eventually become unsustainable.

‘Real world’ situations, including interactions with prey and predators, are essential for understanding ecosystem impacts. Although some organisms within communities appear to thrive under increased CO₂, release from competition pressure may be the main factor responsible.

The potential to acclimate and adapt to high CO₂ varies between species, but we do not yet fully understand the mechanisms involved.

Microbial organisms living in marine sediments (with key biogeochemical roles) may also be impacted by high CO₂. Different major groups, such as bacteria and archaea, respond in different ways.

Ocean acidification does not work alone: it is one of many stressors arising from CO₂ emissions, climate change and other, more direct, human impacts on benthic ecosystems. These effects and their interactions need to be studied together.

Key outputs:

Calosi P, Rastrick SPS, Lombardi C et al. (2013) Adaptation and acclimatization to ocean acidification in marine ectotherms: an in situ transplant experiment with polychaetes at a shallow CO₂ vent system. *Phil. Trans. Roy. Soc. B* 368; art. 20120444; doi: 10.1098/rstb.2012.0444

Findlay HS, Artioli Y, Moreno Navas JMN et al. (2013) Tidal downwelling and implications for the carbon biogeochemistry of cold-water corals in relation to future ocean acidification and warming. *Global Change Biology* 19, 2708-2719; doi: 10.1111/gcb.12256

Godbold JA & Solan M (2013) Long-term effects of warming and ocean acidification are modified by seasonal variation in species responses and environmental conditions. *Phil. Trans. Roy. Soc. B* 368, 20130186; doi: 10.1098/rstb.2023.0186

Hennige SJ, Wicks LC, Kamenos NA et al (2014) Short-term metabolic and growth responses of the cold-water coral *Lophelia pertusa* to ocean acidification. *Deep Sea Research. II: Topical Studies in Oceanography* 99, 27-35

Kamenos NAK, Burdett HL, Aloisio EA et al. (2013) Coralline algal structure is more sensitive to rate rather than the magnitude of ocean acidification. *Global Change Biology* 19, 3621-3628; doi: 10.1111/gcb.12351

Khanna N, Godbold JA, Austin WEN & Paterson DM (2013) The impact of ocean acidification on the functional morphology of foraminifera. *PLoS One* 8, e83118; doi: 10.1371/journal.pone.0083118

Laverock B, Kitidis V, Tait K, Gilbert JA et al. (2013) Bioturbation determines the response of benthic ammonia-oxidising microorganisms to ocean acidification. *Phil Trans Roy Soc B* 368: 20120441; doi: 10.1098/rstb.2012.0441

Queirós AM, Fernandes JA, Faulwetter S et al. (2015) Scaling-up experimental ocean acidification and warming research: from individuals to the ecosystem. *Global Change Biology* 21, 130-143; doi: 10.1111/gcb.12675

Russell BD, Connell SD, Findlay HS et al. (2013) Ocean acidification and rising temperatures may increase biofilm primary productivity but decrease grazer consumption. *Phil. Trans. Roy. Soc. B* 368; art. 20120438; doi: 10.1098/rstb.2012.0438

The UKOA benthic consortium has produced more than 50 peer-reviewed papers to date. **For a complete list see separate hard-copy document or visit www.oceanacidification.org.uk.** All UKOA benthic data is lodged with British Oceanographic Data Centre (BODC).

Cold-water corals: more vulnerable dead than alive?

Cold-water corals have high ecological (and conservation) importance in UK waters. Those living in the shelf seas (water depth ~ 100 m) near Mingulay, North West Scotland benefit from tidal downwelling that brings them warmer, plankton-rich waters.

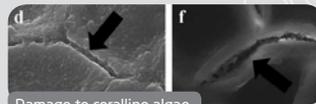


Cold-water coral

That downwelling also dramatically changes water chemistry, resulting in an amelioration of pH impacts in summer – although with risk of greater temperature impacts. Experimental studies of high CO₂ (750 ppm) on the most abundant coral species *Lophelia pertusa* showed no change in calcification rates over 3 weeks when compared to controls; however, their respiration rates decreased, indicating an energetic imbalance. This strategy may not be sustainable on a longterm basis. The main threat is, however, likely to be in deeper waters, where naturally low and declining carbonate saturation states will dissolve dead corals on which the living corals grow, causing the loss of complex reef structures.

Major changes in distribution and habitat complexity of cold water corals may already be underway in the North East Atlantic, but there is a lack of baseline data to assess such effects.

Coralline algae (maerl) are another group of organisms with a key role in habitat structuring, primarily in shallow, coastal water. Experiments with abrupt and slower pH changes showed that the rate and magnitude of change affected their calcification responses. At the faster rate (simulating leakage from a sub-seafloor CO₂ reservoir, as might be used for carbon dioxide capture and storage, CCS), the algal exoskeletons became weaker or began to dissolve so, degrading their structural integrity.

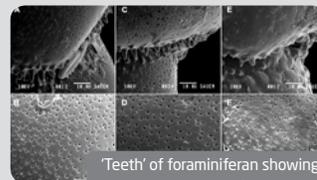


Damage to coralline algae

'Tooth' decay

Foraminifera are single-celled organisms with calcium carbonate shells that can be very abundant in marine sediments. The shells of some species have tooth-like structures that are used for feeding on diatoms (microscopic algae).

Novel UKOA studies, using scanning electron microscopy have shown that high CO₂ conditions (750 and 1000 ppm) could damage the 'teeth', causing breakages, pitting, dissolution and deformities.



'Teeth' of foraminiferan showing progressive damage

Such was the damage at the end of the 9 month study that the specimens were almost unrecognisable to species, with likelihood of major impairment of feeding processes. If this were to happen in the natural environment, the foraminifera would presumably be disadvantaged. Any subsequent reduction in their abundance could lead to knock-on effects at higher trophic levels, affecting carbon cycling and ecosystem productivity.

Responses by communities and individual species

In a 30 day laboratory experiment, the effects of high CO₂/ low pH on marine invertebrate benthic biodiversity, community structure and a selection of functional responses were tested. Artificial substrates (settlement panels) were used to collect standardised communities from the field.

Exposure of these communities to different pH treatments (between pH 8.05 and 6.00) caused significant changes in structure and reduced diversity at reduced pH. The most notable shift was the change in dominance from calcareous to non-calcareous organisms, with numbers of individuals and species changing at pH 7.2 and biomass at pH 7.8. At pH 7.4, net calcification changed to net dissolution, with high mortalities observed at pH 6.0. The study confirmed that elevated pCO₂ is likely to reduce marine biodiversity, with different phyla react differently; such changes would affect community functionality and hence ecosystem services.

Intertidal species live in a highly variable environment, and therefore might be expected to be relatively resilient to environmental changes such as ocean acidification and rising temperature. The velvet swimming crab *Necora puber* had been thought to have such tolerance but UKOA observations and measurements indicated otherwise. Crabs were initially kept in seawater for 14 days at four combinations of temperature (10°C and 15°C) and CO₂ (400 µatm and 1000 µatm). Measurements of key physiological responses were then taken following periods out of water and subsequent recovery from that stress. The high temperature and high CO₂ treatment resulted in slower recovery. Such effects could reduce the intertidal range of this crab, affecting other components of intertidal assemblages.



Periwinkles

UKOA studies on another intertidal invertebrate, the common periwinkle *Littorina littorea* investigated aspects of cellular physiology which might be responsible for changes in an animal's health and behaviour. Measurements were taken of metabolic rates, adenylate energy nucleotide concentration and end product metabolites. In this experiment, higher temperatures reduced, rather than increased, CO₂ effects on metabolic processes, showing the variability - and complexity - of organisms' responses.

Shrimps, microbes and nitrogen cycling

Animals that burrow in muddy marine sediments, such as shrimps and worms, can greatly increase chemical exchanges and nutrient re-cycling.



Burrowing shrimp

Some of these effects are due to microbes living in the burrows. UKOA studies on the mud shrimp *Upogebia deltaura* showed that microbially-mediated ammonia oxidation rates in shrimp burrows were, under non-treated (control) conditions, around five times greater than in surface sediments. However, in acidified treatments (pH values in range 7.9 to 6.8), ammonia oxidation rates in burrows were greatly reduced (by 79%-97%), while rates in surface sediments were unaffected. Changes in shrimp behaviour - increased flushing of their burrows, in response to the decreased pH - are thought to be responsible for the declines in ammonia oxidation. If similar effects were to occur under field conditions, ocean acidification could cause substantial reductions in total benthic ammonia oxidation rates, leading to changes in nitrogen cycling between the seafloor and water column - with implications for the total productivity of shelf seas.

Evolutionary insights from natural laboratories

Benthic biodiversity is much reduced around natural CO₂ vents, where the gas bubbles up from the seafloor causing local ocean acidification. However, some organisms have 'learnt to live with' such conditions, and can provide information on the evolutionary processes involved. UKOA scientists transplanted tolerant (abundant both outside and inside the areas close to vents) and sensitive (living around the vents, but absent in the immediate vicinity of the vents) species of polychaete worm living near a natural CO₂ vent off the island of Ischia, Italy. They showed that one species, *Platynereis dumerelii* was genetically adapted to elevated CO₂, as found close to the vents. However, such adaptation is not ubiquitous among all of the tolerant species found at the CO₂ vents, despite their ecologies appearing similar. A second species *Amphilega mediterranea* showed a marked physiological plasticity to elevated CO₂, so they are acclimatized but not adapted.

Genetic adaptation to elevated pCO₂ has been previously demonstrated in unicellular phytoplankton; this study is one of the first to show that it can also occur in marine invertebrates. The Ischia vent system is thought to be around 2,000 years old; what is not known is how rapidly, or slowly, it took for biological tolerance to ocean acidification to develop during that time period.

A further example of adaptation under natural high CO₂ conditions was observed at another natural seepage site at Vulcano, Sicily. Two species of sea snails, *Nassarius corniculatus* and *Cylope neritea*, living near to the vent were growing more slowly, reaching smaller adult sizes. This is interpreted as a response to having to maintain calcification by adapting their metabolisms, resulting in dwarfism - a phenomenon known as the 'Lilliput effect', seen in the fossil record in many past mass extinctions, and perhaps a sign of things to come as ocean acidification increases.



Benefits of longterm studies

Most experimental studies of ocean acidification impacts are of relatively short-term duration. However, longer-term laboratory studies of the intertidal periwinkle *Littorina littorea* have thrown into doubt the reliability of short-term experiments for the purpose of quantifying the impacts of environmental changes.

UKOA researchers addressed the interaction between 4°C warming and increased CO₂/reduced pH on the grazing rates of periwinkles, following two different periods (5 months and 2 weeks) of pre-exposure to experimental conditions. Results showed grazing rates in animals pre-exposed for 5 months were greater, and they were more sensitive to temperature and CO₂ changes, than 2-week exposed animals. The metabolic rate of the long-exposure group rose with temperature, thus they required more food. In contrast, the 2-week exposure group were metabolically-depressed, and likely to be consuming metabolic reserves. The conclusions are that experimental design can affect results in unanticipated ways, and that short-term studies may be insufficient for assessment of longterm impacts of high CO₂.

In probably the longest combined ocean acidification and warming experiment to date (nearly 16 months), seasonal variation was found to modify the response of the intertidal polychaete *Alitta virens*. It was found that the effects of warming, ocean acidification and their interactions are not detectable in the short term, but became apparent over time through changes in growth, bioturbation and bioirrigation behaviour that, in turn, affect nutrient cycling. These changes are intimately linked

to species responses to seasonal variations in environmental conditions (temperature and photoperiod) that, depending upon timing, can either exacerbate or buffer the long-term directional effects of climatic forcing. Similar effects may be important for other organisms, yet are likely to have been missed in short-term studies.

Another longterm laboratory study (of 14 months) investigated ocean acidification and warming effects for the dogwhelk *Nucella lapillus*. Aspects investigated included physiology, activity, predatory behaviour and susceptibility to predation. Temperature changes were found to have the greatest impact, whilst ocean acidification affected predatory behaviour and response to predation. These experimental results were then combined with information on dogwhelk population dispersal to develop a bioclimatic envelope model, giving projections of the species' potential distribution in the North Atlantic in 2100. The changes were spatially non-uniform and reflected projected local conditions. Scaling-up ecological impact data to make valid projections is a complex process: it requires an integrative approach by experimentalists and modellers in order to produce the most appropriate data for the mathematical models.

Future changes to seaweed distributions

Seaweeds (macro-algae and seagrasses) have fundamental ecological importance as primary producers and habitat-formers in intertidal zones and shallow coastal ecosystems. A synthesis study of all available information on the responses of north east Atlantic seaweeds to acidification and temperature change indicated that major shifts in species' distributions and abundances are likely over the next 50-100 years, on the basis of continued current trends for CO₂ emissions. Thus further ocean warming is expected to cause the loss of kelp forests in Spain, whilst maerl beds are at risk in Norway, as a result of reduced pH (and associated low carbonate saturation states). However, seagrasses are likely to proliferate, with other organisms growing on them (epiphytes) altering from calcified algae to diatoms and filamentous species. The likely loss of native species will encourage invasives (e.g. from the Pacific) to thrive, aided by warmer temperatures and ice-loss in the Arctic, more trans-Arctic shipping, and the increase of artificial marine structures in coastal waters. The combined effects of ocean acidification, warming and an increase in storminess may replace structurally diverse seaweed canopies with simpler habitats dominated by non-calcified, turf-forming species.



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.

The acidity (H⁺ concentration) of the surface ocean has already increased by nearly 30% due to these events, mostly in the past 50 years. If future CO₂ releases continue to follow current global trends, by 2100 ocean acidity will increase by as much as 150%, at a rate of change 10 times faster than at any time in at least the last 65 million years. Such a major alteration in ocean chemistry will have (and is already having) wide implications for marine life.

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, food-webs 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.

