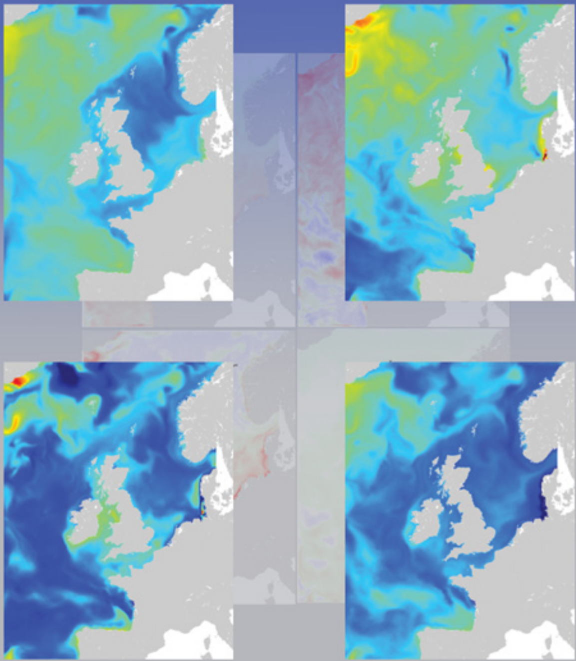
UK Ocean Acidification Research Programme

UK Ocean Acidification programme synopsis

Regional and global modelling



www.oceanacidification.org.uk

Ocean acidification parameters, processes and projections

Mathematical modelling has an increasingly important role in environmental science, now providing the main tool for developing and testing understanding of complex, interacting processes. For ocean acidification, models link water chemistry with global-scale changes in atmospheric composition and climate; with water circulation patterns; and with physiology, ecology, biogeochemistry and socio-economics. A common feature is the involvement of quantitative descriptions – and the need to develop projections of possible futures (forecasting) or simulating past events (hindcasting). Environmental models are rarely predictive, in the sense of defining deterministic outcomes, but are inherently probabilistic, simulating scenario-based possibilities.

Two UKOA consortia, with complementary approaches, looked at how modelling could assist in exploring the processes and potential impacts of ocean acidification. Although initially described separately (below), their outputs and activities are here subsequently considered together.

The consortium **Regional ecosystem and biogeochemical impacts of ocean acidification** was led by Jerry Blackford at Plymouth Marine Laboratory, with partners at the National Oceanography Centre (Liverpool and Southampton) and close links with the Meteorological Office/Hadley Centre. Research effort focussed on ocean acidification processes and impacts in European and Arctic shelf seas. Projection of future conditions for regional shelf seas is challenging, since the relevant physical, chemical and biological dynamics are all strongly linked, with high spatial heterogeneity, and also affected by human activities.

The main aim was to use modelling to develop novel, scientific knowledge of the magnitude and timescale of risks of both ocean acidification and climate change for regional seas. This would be achieved through four scientific objectives:

- Improving certainty in predictions of carbonate chemistry in shelf seas, other key indicators and ecological niche distribution
- Providing an improved quantification and understanding of the exchange of carbon (dioxide) between shelf and oceanic environments
- Quantifying the range of ecosystem consequences arising from ocean acidification and co-drivers
- Generate a step-change in the UK modelling capability of Arctic coupled bio-physical systems.

The consortium **CO_2 – carbon cycle – climate interactions** was led by Andy Ridgwell at Bristol University in partnership with Cardiff University.

A range of topics was covered, with particular attention given to the following research areas:

- Address critical gaps in our understanding of the modern ocean carbon cycle, including:
- The role of calcifying plankton in assisting the downward fluxes of organic and inorganic material, and the potential influence of ocean acidification on such processes.
- The importance of carbonate saturation state in constraining coral distribution and abundance
- Build directly on this to make projections of the range of potential changes we might see in ocean carbon and nutrient cycles in the future, and whether these changes will affect the degree of future warming by positive (or negative) feedback processes.

Outputs include:

Artioli Y, Blackford JC, Nondal G, Bellerby RGJ, Wakelin SL, Holt JT, Butenschön M & Allen JI (2013) Heterogeneity of impacts of high CO_2 on the North Western European Shelf. Biogeosciences, 11, 601-612; doi: 10.5194/bg-11-601-2014

Couce E, Ridgwell A & Hendy EJ (2012) Environmental controls on the global distribution of shallow-water coral reefs. Journal of Biogeography 39, 1508-1523

Couce E, Ridgwell A & Hendy EJ (2013), Future habitat suitability for coral reef ecosystems under global warming and ocean acidification. Global Change Biology 19, 3592-3606, doi: 10.1111/gcb.12335 (2013).

Couce E, Irvine PJ, Gregorie LJ, Ridgwell A & Hendy EJ (2013) Tropical coral reef habitat in a geoengineered, high-CO_2 world, Geophysical Research Letters 40, doi:10.1002/grl.50340.

Hönisch B, Ridgwell A, Schmidt DN, Thomas E, Gibbs SJ, Sluijs A, Zeebe R, Kump L, Martindale RC, Greene SE, Kiessling W, Ries J, Zachos JC, Royer DL, Barker S, Marchitto TM, Moyer R, Pelejero C, Ziveri P, Foster GL & Williams B (2012) The geological record of ocean acidification. Science 335, 1058 -1063; doi: 10.1126/science.1208277

Jones NS, Ridgwell A & Hendy EJ (2015) Evaluation of coral reef carbonate production models at a global scale. Biogeosciences 12, 1339-1356.

Popova EE, Yool A, Aksenov Y, Coward AC & Anderson TR (2014) Regional variability of acidification in the Arctic: a sea of contrasts. Biogeosciences 11, 293-308; doi: HYPERLINK "http://dx.doi.org/10.5194/bg-11-293-2014" \t "_blank" 10.5194/bg-11-293-2014.

Wakelin SL, Holt JT, Blackford JC, Allen JI, Butenschön M & Artioli Y (2012) Modeling the carbon fluxes of the northwest European continental shelf: Validation and budgets. Journal of Geophysical Research 117, C05020; doi: 10.1029/2011JC007402.

Wilson JD, Barker S & Ridgwell A (2012) Assessment of the spatial variability in particulate organic matter and mineral sinking fluxes in the ocean interior: implications for the ballast hypothesis. Global Biogeochemical Cycles 26, art. GB4011, doi:10.1029/2012GB004398.

Wilson JD, Ridgwell A & Barker S (2015) Can organic matter flux profiles be diagnosed using remineralisation rates derived from observed tracers and modelled ocean transport rates? Biogeosciences Discussion, 12, 4557-4593, doi:10.5194/bgd-12-4557-2015.

Wood S, Paris CB, Ridgwell A & Hendy EJ (2014), Modeling dispersal and connectivity of broadcast spawning corals at the global scale. Global Ecology and Biogeography 23, 1-11.

Yool, A., Popova, E. E., and Anderson, T. R (2013) MEDUSA-2.0: an intermediate complexity biogeochemical model of the marine carbon cycle for climate change and ocean acidification studies. Geoscience Model Development 6, 1767-1811, doi:10.5194/gmd-6-1767-2013, 2013.

For full list of publications arising to date from this component of the UKOA programme, see separate hard-copy document or online at www.oceanacidification.org.uk

Interactions of ocean acidification and climate change

Increasing atmospheric CO_2 presents the dual threat to the marine environment of climate change and ocean acidification. The response of the ecosystem to a single driver can be variable and complex, and remains uncertain; when two drivers occur together, their combined effects can be synergistic (reinforcing) or antagonistic (opposing).

To study the interaction between climate change and ocean acidification, modellers used the coupled POLCOMS-ERSEM model driven by climate forcing and focussing on carbonate chemistry, primary and secondary production. Although the projected global mean pH by the end of the century would fall by 0.27 units (under a high CO_2 emission scenario), the models indicate that the drivers interact, with high variability in both time and space. This means that critical tipping points may be reached at different times in different locations. The models also project that the impacts of climate change and acidification are likely to be similar in magnitude, but in some areas together they will exacerbate impacts, while in others they may ameliorate effects. So, for example, acidification might enhance productivity, while climate changes might reduce it, or increased primary production in coastal areas due to high CO_2 might lead to reduced acidification in the same area.

This shows that single driver responses can be cancelled out or enhanced by feedback from another driver or process. So there is a need for ecosystem and multi-driver approaches in the study of global changes.

The model also highlighted the heterogeneity of marine system and the requirement to take variability in physical and biological processes into account when modelling ecosystem responses to global changes.

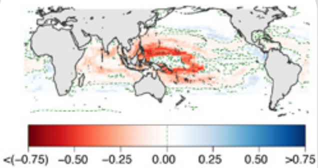
Coral futures

Tropical coral reef communities play an important role in the global carbon cycle: they account for half of the carbonate produced in shallow water environments and more than a quarter of the total carbonate buried globally, so any threat from ocean warming and/or ocean acidification is potentially serious.

Modelling calcification
Understanding how tropical corals may respond to environmental changes requires numerical models. However, before looking to the future, a fundamental test of the skill of such models is to test them against known present-day calcification rates. A significant project outcome was the compilation of an independent, observation-based, global database on tropical reef calcification, for model evaluation of carbonate budgets outputs. UKOA researchers tested four models based on functions sensitive to combinations of available light, aragonite saturation and temperature. None of the models could reproduce the independent estimates of calcification, while the temperature-only approach was the sole model to correlate with observed coral calcification.

A conclusion from this work is that in order to make sensible predictions more ecosystem data (including mortality, recruitment, and abundance of calcifying organisms) are needed.

Where can tropical corals go?
Bioclimatic envelope models have been used to determine potential future distributions of animals and plants in a changing world. The principle is simple: measure the environmental parameters where an organism lives at present, project parameter changes as they will be altered in a changing world and plot where suitable conditions might allow future survival. This modelling approach was applied by UKOA researchers to tropical corals, threatened by rising sea temperatures and ocean acidification. The models projected major declines in suitable habitat for many existing coral regions, particularly the central Indo-Pacific, accompanied by an accelerating poleward range expansion of suitable conditions, by as much as 70 km per decade by 2070. However, the ability of corals to exploit these replacement conditions will depend on their dispersal capabilities, as well as other environmental factors (such as shallow water, adequate light penetration and lack of pollution). Model projections of ocean acidification suggest it is less influential than warming.



Projected change in environmental suitability for coral reef ecosystems between 1990 and 2070 under the effects of warming and acidification expected for the A2 emission scenario. Environmental suitability is measured from 0 (not suitable at all) to 1 (optimal conditions for coral reefs)

Contrary to expectation, the combined effect of acidification and warming appears to lead to little degradation in the suitability of habitats in the future over much of the Atlantic and in those areas considered to be currently on-the-edge for tropical coral survival, e.g. the eastern Equatorial Pacific. In this area, cooler water apparently limits corals; thus any warming would encourage expansion, and might outweigh any effects from ocean acidification.

North Sea may become corrosive for carbonate

If we are to understand impacts of ocean acidification in societally-important shelf seas we first have to have a clearer idea of how the carbonate system works. High resolution hydrodynamic and ecosystem models coupled together provide a method of capturing the spatial and temporal heterogeneity of these areas, but are they reliable? UKOA modellers coupled the POLCOMS-ERSEM model with the added parameter of alkalinity and explicitly accounting for river inputs and biological activities.

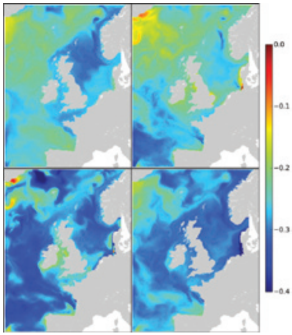
By comparing the model outputs with North Sea observational data (from the CANOBA project), they validated the approach. Thus the model demonstrated good to reasonable agreement for all principle variables, including temperature, salinity, nutrients, dissolved inorganic carbon and total alkalinity. Scope for improvement was identified for the derived variables of pH and pCO_2, due to uncertainties in riverine inputs and primary production.

The coupled models were used to provide projections, to 2100, of future ocean acidification and carbonate saturation state for the northwest European shelf, using a high CO_2 emissions scenario (A1B developed by the Intergovernmental Panel on Climate Change), consistent with current trends. The model outputs showed fine-scale spatial variability (reflecting hydrodynamics), strong seasonality, and large differences between sea surface and seafloor conditions in stratified waters. Biological processes were found to be particularly important in the simulations, defining the seasonality of the impact. In the areas where an increase in net primary production is projected, a relatively lower acidification is simulated by the model (e.g. in spring in the North Atlantic or in the southern North Sea in summer).

Seasonal undersaturation of aragonite is projected for ~30% of bottom waters of the North Sea, as a consequence of decomposition of organic material near the seafloor, releasing CO_2. Such waters would then become corrosive for unprotected shells and other exoskeletons using that form of carbonate.

Future changes to global ocean productivity

Using the MEDUSA -2.0 global model, UKOA researchers examined the large-scale response of ocean biogeochemistry to future ocean acidification and climate change. They found that the main impact would arise from decreased nutrient availability in surface waters, due to reduced mixing (stronger stratification). This change is projected to lead to a net 6.3% global decline in ocean productivity by the 2090s compared to the 1990s. The impact is expected to follow on through trophic levels up to fish and hence fisheries. In parallel there is a projected large reduction in the amount of organic material exported downwards to seabed communities, and an increase in the volume of oxygen depleted zones. Ocean productivity impacts are likely to be spatially variable, with a projected decline of 21% in the Atlantic, but an increase of 59% in the Arctic.



Impacts of climate change and OA on the carbonate system as projected by the A1B scenario: absolute difference in surface pH compared to the present-day

As with any modelling approach, these projections rely on understanding the underlying processes, and it is recognised that there is still much room for improvement in that regard. For example, the role played by calcifying organisms in 'ballasting' organic carbon, from the surface to the seabed.

Variability in the Arctic

The Arctic Ocean is particularly vulnerable to the impact of ocean acidification, with potentially negative consequences for calcifying organisms such as pteropods, coccolithophores and foraminifera. UKOA researchers used a high-resolution, ocean-only general circulation model, with embedded biogeochemistry and a comprehensive description of the ocean carbon cycle, to study the response of pH and carbonate saturation state to rising atmospheric CO_2 and changing climate in the Arctic. Simulations were run to 2100 using a high emissions scenario (RCP 8.5, developed by the Intergovernmental Panel on Climate Change).

The direct impacts of the increase in atmospheric CO_2 were separated from indirect impacts via climate change and its consequences (changing temperature, stratification, primary production and freshwater fluxes) by undertaking two simulations, one with the full system and the other in which atmospheric CO_2 was prevented from increasing beyond its pre-industrial level (280 ppm). Results indicate that climate change impacts, and their spatial heterogeneity, will play a strong role in the declines in pH and carbonate saturation projected for the Arctic. The central Arctic, Canadian Arctic Archipelago and Baffin Bay show greatest rates of acidification as a result of melting sea ice. In contrast, areas affected by Atlantic inflow including the Greenland Sea and outer shelves of the Barents, Kara and Laptev seas, seem likely to experience less acidification because diminishing ice cover results in greater vertical mixing and primary production. As a consequence, the projected onset of carbonate undersaturation in respect to aragonite is highly variable within the Arctic, occurring during the decade of 2000–2010 in the Siberian shelves and Canadian Arctic Archipelago, but as late as the 2080s in the Barents and Norwegian seas. Whilst it is clear that regional variability of ocean acidification in the Arctic is significant, and needs to be adequately resolved, rates of retreat of sea ice remain a major source of uncertainty.

Ballasting doesn't explain everything

Carbon movement to the ocean strongly affects climate feedbacks – and where ocean acidification effects will occur, and their severity. Key questions relate to the transport of organic material from the surface to ocean interior, and how quickly it is degraded by bacteria. If this decomposition happens in the ocean depths, carbon is effectively locked away for a millennium or more; if close to the surface, CO_2 may be released back to the atmosphere, contributing to further global warming. Yet despite being represented in global models, questions remain with regard to how far the organic carbon sinks, what controls its movement to depth, and what dominates its degradation. Different models are based on different assumptions, each of which might be affected by ocean acidification, warming, or a combination of both, or neither UKOA researchers focussed on the assumption that 'ballasting' provides the means by which organic material sinks (at around 100 m per day) to the depths. The ballast is the calcium carbonate ($CaCO_3$) shells, tests and liths formed by the plankton, that are about three times the density of seawater.

The concern is that ocean acidification could reduce calcification and decrease the size or thickness of the carbonate particles, slowing sinking and keeping CO_2 near the surface. How much of this ballast gets to the seabed has been measured in sediment traps, rather like rain gauges. The problem is that there are not very many of these traps, and so global models are based on extremely patchy data and cannot explain the relationships between some sets of variables. In the UKOA study, a geographical regression model was used to reveal the relationships that exist between variables by using all the data that was available. Huge variation was found in the statistical relationship between organic matter and $CaCO_3$ ballast, by as much as an order of magnitude; furthermore, in areas where ballasting might be expected to be high, it was of least importance. This work does not rule out ballasting – but it does show that it is not the single globally uniform mechanism that many models have assumed. Thus a greater spatial spread of observations is needed if new models are to begin to project with any certainty the biogeochemical impacts and feedbacks of ocean acidification and warming.

UK Ocean Acidification Research Programme

What is ocean acidification?

The global ocean currently absorbs more than a quarter of the CO_2 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 CO_2 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 CO_2 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.

NERC Science of the Environment
Department for Environment Food & Rural Affairs
Department of Energy & Climate Change
Living With Environmental Change

Boot KJ, Blackford J, Ridgwell A, Yool A, Popova E, Couce E, Turley C, Williamson P (2015) UK Ocean Acidification programme synopsis: Regional and global modelling. UKOA/PML