The UK Ocean Acidification Research Programme - Implementation Plan (2009-2014)

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1. Summary

This *Implementation Plan* details the method of execution of the *UK Ocean Acidification Research Programme*, the science of which is laid out in the Research Programme's *Science Plan*. It addresses the requirements placed on the programme by the funders – NERC, Defra and DECC. This plan describes the implementation of the seven main *Science Deliverables* in the 5 year research programme and the mechanisms for exploitation of the knowledge gained in these areas to inform policy and societal need for a greater understanding of the implications of ocean acidification and its risks to ocean biogeochemistry and biodiversity and impact on the whole Earth System.

2. Introduction

The NERC Strategy, launched in November 2007, identified ocean acidification as one of its challenges and this was expanded upon in the Earth System Science and Biodiversity Theme Action Plans (http://www.nerc.ac.uk/research/themes/tap/). In 2008 NERC approved a £7.7M, 5 year NERC Large-Scale Programme on ocean acidification to enable NERC to deliver its Strategy. This was evaluated and supported by SISB and by Council. The UK Government Departments, Defra and DECC, had also been developing their plans for implementation of research on ocean acidification in order to deliver the UK Government's Strategic Objectives with respect to adapting to and mitigating climate change and ensuring a healthy, resilient, productive and diverse natural environment. NERC, Defra (£3.3M) and DECC (£1M) have pooled their investment in the now jointly funded £12M *UK Ocean Acidification Research Programme* which will run for five years from 2009-2014.

3. The Research Programme's Objectives

a. To reduce uncertainties in predictions of carbonate chemistry changes and their effects on marine biogeochemistry, ecosystems and other components of the Earth System.
b. To understand responses to ocean acidification and other climate change related stressors by marine organisms, biodiversity and ecosystems and to improve the understanding of their resistance or susceptibility to acidification.
c. To provide data and effective advice to policy makers and managers of marine bioresources on the possible size and timescale of risks to allow for development of appropriate mitigation and adaptation strategies.

4. The Research Programme's Main Science Deliverables

The above programme *Objectives* will be achieved through seven *Science Deliverables (Objectives a and b)* and extensive knowledge exchange, science co-ordination and outreach activities *(Objective c).*

The seven *Science Deliverables* from the *UK Ocean Acidification Research Programme* are:

1: Improved estimates of ocean CO_2 uptake and associated acidification.
2: Improved understanding of the impact of ocean acidification on surface ocean biology, community structure, biogeochemistry and on feedbacks to the climate.
3: Identification and improved understanding of the potential impacts and implications of ocean acidification on key benthic ecosystems, communities, habitats, species and life cycles.
4: Improved understanding of the potential population, community and ecosystem impacts

for all life stages for commercially important species and their capacity to resist and adapt.
5: Provision of evidence from the palaeo record of past changes in ocean acidity and resultant changes in marine species' composition and Earth System function.
6: Improved understanding of the cumulative/synergistic effects of ocean acidification and other global change pressures on ecosystems, biogeochemical cycles and feedbacks on climate through modelling activities.
7: A service for carbonate chemistry measurements.

These *Science Deliverables* are detailed in the programme's *Science Plan* and each will be implemented as specified below at the approximate funding level and through the grant type indicated.

Science Deliverable 1: Improved estimates of ocean CO_2 uptake and associated acidification.
Aim 1.1 To quantify the rate of progression of ocean acidification in the North-East Atlantic (including European shelf and slope), Southern and Arctic Oceans, including identification of when/where $CaCO_3$ undersaturation will occur first.
Aim 1.2 To quantify spatial and/or seasonal variability of carbonate system parameters in these areas.
Aim 1.3 To improve quantification of the rate of oceanic CO_2 uptake in these areas.

It is anticipated that this deliverable will be implemented through a single co-ordinated grant of around £650K.

Monitoring of ocean acidification and ocean CO_2 uptake should be carried out on repeat routes and/or through time series. UK institutions already monitor ocean carbon in a few places and along a few routes. Surface water pCO_2 alone is measured in some cases, whereas two carbonate chemistry parameters are measured elsewhere. In order to address *Aim 1.1*, a mandatory requirement for monitoring within this programme is the simultaneous measurement of at least 2 parameters of the carbonate system together (but not pCO_2 and *p*H as a pair; see section 5) with accurate measurements of temperature and salinity, such that seawater *p*H, $[CO_3^{2-}]$, and $CaCO_3$ saturation states can be derived. The aims may be achieved either by augmenting existing routes with an additional carbonate system parameter, by continuation of existing routes/time-series where two parameters are already measured, or by initiation of new routes/time-series on which two or more parameters will be measured. Bids for funding should quantify the accuracy of the analyses of carbonate system parameters.

Science Deliverable 2: Improved understanding of the impact of ocean acidification on surface ocean biology, community structure, biogeochemistry and on feedbacks to the climate.
Aim 2.1 To ascertain the impact of ocean acidification on planktonic organisms, both in terms of physiological impacts and also population abundances and community composition.
Aim 2.2 To quantify the impacts of ocean acidification on biogeochemical processes affecting the ocean carbon cycle, including via availability of bio-limiting nutrients.
Aim 2.3 To determine impacts of ocean acidification on the air-sea flux of climate active gases and on the composition of organics in the microlayer.

It is envisaged that a single co-ordinated consortium of approximately £3M (around £1.1M for *Aim 2.1*, £1.1 M for *Aim 2.2* and £0.8M for *Aim 2.3*) will address the whole deliverable.

Important approaches include *in situ* observations, on-deck incubation experiments, mesocosm experiments, laboratory experiments, and modelling. This deliverable will require a large ship-based component, with at least three cruises to the polar oceans and the North-East Atlantic and/or adjacent shelf seas, using NERC's research ships and potentially other available vessels. Modelling should link to the Hadley Centre marine modelling work, where appropriate, and should be complementary to (build upon) ongoing modelling activities within BIOACID (**B**iological **I**mpacts of **O**cean **Acid**ification), the EU programmes EPOCA (***E**uropean **P**roject on **Oc**ean **A**cidification*) and MEECE (**M**arine **E**cosystem **E**volution in a **C**hanging **E**nvironment). Mesocosm work should be through collaboration as the procurement of any large-scale facilities is excluded from this programme.

Experimental studies (laboratory-based and ship-board) should follow best practice (Riebesell *et al.* 2009, Rost *et al.* 2008, Orr *et al.* 2009) and comply with standards and guidelines given in section 5 and should also be carried out at realistic carbon, alkalinity, Ca and Mg concentrations. More robust conclusions can be drawn from experiments if it is possible to extend them beyond mono-cultures to include interactions within and between trophic levels (Rost *et al.* 2008) as such more complex experiments are encouraged. Proposals should not duplicate (unless this can be fully justified) any experiments carried out in BIOACID. It is advantageous if experiments can assess synergistic effects, e.g. ocean acidification effects in conjunction with other global change variables, such as temperature, nutrients and anoxia.

Observational studies must measure both biogeochemical rates, e.g. calcification, photosynthesis, nitrogen fixation, carbon export, and standing stocks, e.g. PIC, POC, chlorophyll, *Trichodesmium* abundance, plankton species abundances and community structure (of bacteria, phytoplankton, zooplankton and planktonic larvae), morphology of calcifiers (including size normalised forminiferal shell weight) and both concentrations and rates of production/consumption of climate-relevant gases. Study of the possible impact of ocean acidification on the composition and activity of organics in the microlayer should be aimed at soluble surface active compounds and could investigate the impact on either aerosol production or gas transfer rates, or both. *In situ* measurements should be made in regions with natural differences in carbonate chemistry, noting that in places these can be as high as those associated with a doubling of atmospheric CO_2 (Rost *et al.* 2008). Sampling along carbonate chemistry gradients should be carried out in multiple, diverse locations, in order to assess robustness of observed correlations with carbonate chemistry and the degree to which such correlations could alternatively be explained by co-variance of other parameters.

The outputs of *Science Deliverable 5* should be linked to this Deliverable (see *Science Deliverable 5* in the *Implementation Plan* for further details.)

Science Deliverable 3: Identification and improved understanding of the potential impacts and implications of ocean acidification on key benthic ecosystems, communities, habitats, species and life cycles.
Aim 3.1 To determine the effect of ocean acidification on the performance, life history and population dynamics of individual benthic species, with preference given to those species likely to influence overall benthic ecosystem function.
Aim 3.2 To quantify the impacts of ocean acidification on biogeochemical cycling of key nutrients within sediments and their exchange with the seawater column.
Aim 3.3 To determine the effects of ocean acidification on the overall function of key benthic habitats.

It is envisaged that a single large consortium, of approximately £2M (around £750K for *Aim 3.1*, £750K for *Aim 3.2* and £500K for *Aim 3.3*) will address the whole topic in a coordinated manner.

It is anticipated that these three aims will require experimental work on individual species or, where feasible, particular assemblages, such as deep-water coral reefs, maerl beds or seagrass. In addition to detailed studies of the calcification process itself, proposals should include measurements of other metabolic parameters. Consideration will be given to comparative work on calcifying and non-calcifying species, and to achieving a mechanistic understanding of how changes in ocean acidification and temperature will impact the physiology, behaviour and function of key organisms and assemblages. Projects should link with, or directly complement, studies being undertaken within the BIOACID and EPOCA projects. It is expected that studies will be targeted at species, assemblages and habitats that are of relatively easy access, such as coastal locations, or vulnerable. Proposals that use genomic techniques are encouraged, with preference given to species that have been, or soon will be, sequenced.

Benthic laboratory studies should adopt best practice (e.g. Rost *et al.* 2008, Havenhand 2009,; Widdicombe *et al.* 2009) as outlined in section 5. Benthic experiments should be conducted over longer time periods (months to years) than is generally possible for pelagic experiments, so as to test whether responses to ocean acidification are limited to the short term only. It is advantageous if experiments can assess synergistic effects, e.g. temperature, light, nutrients and, where appropriate, anoxia, in combination with ocean acidification, where logistically feasible. Fieldwork, including research cruises, is anticipated and should focus on shelf seas and shelf edge, particularly in areas where strong gradients in carbonate chemistry are likely.

Close collaboration with *Science Deliverable 5* should be established for analysis of shells and skeletons of organisms exposed to a variety of CO_2 and carbonate ion conditions (see *Science Deliverable 5* in the *Implementation Plan* for further details.)

Modelling activities from this deliverable will collaborate with global and regional modelling within *Science Deliverable 6*.

Science Deliverable 4: Improved understanding of the potential population, community and ecosystem impacts for all life stages for commercially important species and their capacity to resist and adapt.
Aim 4.1. To examine the physiological and behavioural responses of commercial fish and shellfish to ocean acidification and their capacity to resist and adapt.
Aim 4.2. To 'scale up' from laboratory studies to population and stock level responses to ocean acidification including an analysis of possible socio-economic consequences.
Aim 4.3. To examine how changes in planktonic and benthic food-webs, as a result of ocean acidification, impact upon the production and yields of commercial fish and shellfish stocks.
Aim 4.4. To investigate the possible socioeconomic consequences relating to ocean acidification at an ecosystem level.

This deliverable should be realised through a single co-ordinated grant of around £700K to address Aims 4.1, 4.2, 4.3 with a module to cover Aim 4.4 at an additional £200,000.

Much of the focus under this *Science Deliverable* will be on commercially relevant species and ecosystems that are associated with the UK shelf seas. It is anticipated that some laboratory work will be required in order to parameterize population and ecosystem models

and to investigate the direct physiological consequences of an increase in oceanic CO_2 and/or a lowering of *p*H for commercial fin-fish and shellfish species. This research will be clearly focused and will contribute directly to Defra's long-term commitments on sustainable resource management. Experiments will necessitate a high degree of control over water quality, temperature and pCO_2, and it is anticipated that multiple life-history stages (larvae, juveniles, adults) will be reared, in order to examine impacts throughout each animal's life cycle. Experiments should be designed to complement and not replicate, those being conducted elsewhere, most notably under the BIOACID initiative, but also those of fisheries agencies in the USA (NMFS/NOAA) and Canada (DFO/BIO). The focus of laboratory studies should be guided by the needs of the population models, thereby allowing researchers to 'scale up' from their investigations and attempt to predict implications for fin-fish and shellfish stocks in the wild, as well as future fishery yields.

In addition to single species population modelling, research will be required into complex food-webs. Such studies should link to ongoing modelling activities within national and EU programmes including RECLAIM (**Re**solving **Cl**im**a**tic **Im**pacts on Fish Stocks), UNCOVER (**Un**derstanding the Mechanisms of Stock Re**cover**y) and MEECE. The aim of this modelling work will be to elucidate how impacts of ocean acidification in the benthic and/or planktonic part of the food-web proliferate to other ecosystem components, including species at higher trophic levels such as fish, marine mammals and seabirds. It is hoped that modelling will reveal which commercial and conservation species might suffer most under various future scenarios and consequently which fishing fleets and/or aquaculture operations might be affected. It will be expected that modelling within *Science Deliverable 4* will link with and inform global and regional modelling within *Science Deliverable 6.*

Science Deliverable 4 will involve a preliminary analysis of the possible socio-economic consequences of ocean acidification, including the valuation of ecosystem 'goods and services' and how these might be affected in the future. This work will require that the successful consortium includes a team of researchers from a variety of different academic disciplines, including experimental ecologists, modellers and socio-economists.

Science Deliverable 5: Provision of evidence from the palaeo record of past changes in ocean acidity and resultant changes in marine species' composition and Earth System function.
Aim 5.1. To determine whether historical changes in carbonate ion concentration and *p*H since industrialisation have already had discernible impacts on the calcification of marine organisms.
Aim 5.2. To ascertain the maximum rate and amplitude of ocean acidification to which species and ecosystems can adapt and the threshold of acidification that would lead to enhanced evolutionary turnover and extinction of species.
Aim 5.3. To assess suitability of museum collections for palaeo study of ocean acidification.

It is anticipated that this deliverable will be attained through two projects of approximately £550K, each project addressing one of the *Aims 5.1* and *5.2*, and a direct contract (around £50K) with the Natural History Museum (*Aim 5.3*).

To achieve *Aim 5.1* it is necessary to document possible biotic changes or the lack thereof in marine calcifiers as a result of the post-industrial rise in atmospheric CO_2 (100 ppm since 1800, 60 ppm since 1960). These biotic changes could include, amongst others, possible dissolution features and/or calcification changes in specimens from historical collections compared to modern specimens taken at the same location. Possible changes in assemblage

composition of planktonic flora and fauna linked to changes in palaeo temperature and carbonate ion will provide important information for *Science Deliverable 2*.

Regional geochemical modelling and data may be necessary to link changes in calcification with changes in carbonate ion and *p*H and other environmental parameters. Close collaboration with *Science Deliverables 2 and 3* for analysis of shells and skeletons of organisms exposed to a variety of CO_2 and carbonate ion conditions is highly desirable, and will be instrumental in calibrating and verifying the shell/skeletal evidence of impacts on calcification.

Aim 5.2 will improve our knowledge of the carbonate ion or *p*H changes during past abrupt ocean acidification events. A multi-proxy approach involving trace element ratios and isotope proxies should be applied to analysis of a wide range of carbonate system parameters. These proxies may include Zn/Ca (Marchitto 2000), B/Ca (Yu & Elderfield 2007, Yu *et al.* 2007), $\delta^{11}B$ (Kasemann 2009) potentially linked with well quantified biotic proxies such as size normalised shell weight (Barker 2002). Ocean acidification leads to dissolution of carbonate and, hence, the limited number of sections which yield enough material, combined with the suboptimal preservation state of proxy carriers, will pose analytical challenges. Therefore, an essential prerequisite is a proven record of application of analytical approaches capable of dealing with extremely small amounts of material, to provide reliable data on carbonate ion changes in surface and deep water. Alternative environmental factors, such as temperature, have to be quantified to shed light on synergetic/competing effects on species and ecosystems. These data will allow links between biotic change and patterns of reorganisation and recovery of the carbonate system to be constrained. The results will link to *Science Deliverable 2, Aim 2.1 and Science Deliverable 6, Aim 6.1* via changes in biogeochemical cycles, such as the biological and alkalinity pumps.

To achieve *Aim 5.3* a review will be undertaken to assess the potential novel use of historical collections for ocean acidification studies. This review will focus on the Natural History Museum (NHM), as the museum contains the largest collections of pre-industrial specimens (including deep sea sediment samples), but will also include a systematic overview of relevant collections in other UK museums, e.g. Liverpool and Newcastle, and research institutes, e.g. BAS and BGS). This will deliver a collections level database of holdings of material suitable for ocean acidification research within *Aims 5.1 and 5.2*, i.e. of marine biocalcifying organisms with known collection date and location, collected prior to 1965 and ideally pre-1900. Relevant information will include scale and scope of collections; nature of material and method of storage; geographical area and date of collection; quality of location and date information; availability of material for destructive analysis and suitability of material for faunal or floral analysis.

Science Deliverable 6: Improved understanding of the cumulative/synergistic effects of ocean acidification and other global change pressures on ecosystems, biogeochemical cycles and feedbacks on climate through modelling activities.
Aim 6.1. To improve understanding of the combined impacts of ocean acidification and other global change pressures on ecosystems, biogeochemical cycles and feedbacks on climate at the global scale.
Aim 6.2. To improve understanding of the combined impacts of ocean acidification and other global change pressures on regional ecosystems and biogeochemical cycles through modelling activities.

This deliverable should be addressed by two projects of around £300K, each project addressing one of the aims.

Aim 6.1 requires the examination of the potential combined impacts of ocean acidification and other large-scale drivers (temperature, ocean circulation, stratification, etc) on ecosystems, biogeochemical cycles, e.g. C and N cycling, flux of climatically active gases, extent of the biological pump, export production, recycling in thermocline, and climate feedbacks, at the global scale (links to *Science Deliverable 2 and 3* should be made). Building on established modelling activities, ongoing process studies and the palaeo record (links to *Science Deliverable 5* should be made), the project should seek to improve understanding and prediction of the consequences of a high CO_2 world. Specifically, it should provide an assessment of the combined impacts of ocean acidification and other global change pressures under different scenarios of future greenhouse gas emissions. Ideally, both 'mitigated' and 'unmitigated' emission scenarios should be considered, with a view to understanding the impacts and risks that would be avoided by implementing emission mitigation measures. The work will contribute to establishing whether ocean acidification is significant in the context of the Earth System and contribute to the next IPCC Assessment Report on climate change.

Aim 6.2 requires the examination of the regional impacts (North-East Atlantic including the North-West European Shelf and/or the Arctic seas) of ocean acidification, together with other climatic and anthropogenic drivers of biogeochemical cycles and whole ecosystem structure and function (plankton and higher trophic levels from modelling within *Science Deliverables 1 and 4*). The project should seek to establish the dominant drivers affecting marine ecosystems under different scenarios of future greenhouse gas emissions and whether these effects are cumulative or synergistic. Building on established model systems, the role of changing ice cover, terrestrial inputs (carbon and nutrients), cross shelf exchange and the benthos should be considered. The recent past should be considered as well as an exploration of the potential future envelope of response. Again output would contribute to future regional IPCC assessments of climate change.

Links to modelling activities at the Hadley Centre, the German project (BIOACID) and the EU projects (EPOCA and MEECE) are strongly encouraged where appropriate. It is expected that these activities will work closely with chemists, physiologists, ecologists, fisheries biologists, biogeochemists and palaeo-oceanographers within the *UK Ocean Acidification Research Programme* to enable a co-ordinated iteration between modelling, laboratory experiments, mesocosm CO_2 manipulation experiments, *in situ* observations and analysis of long-term and palaeo records.

Science Deliverable 7: A service for carbonate chemistry measurements
Aim 7.1. To provide high quality carbonate chemistry measurements across the programme.

This deliverable should be provided by one co-ordinated project of around £400K, preferably involving more than one institution to ensure UK capacity growth in this area.

Bids will be invited to provide a measurement service capable of analyzing 10,000 samples over 4.5 years (to finish 6 months before the end of the research programme, by which time data collection should have finished), for three separate parameters, e.g. DIC, Alkalinity and *p*H (via a spectrophotometric technique). Bids should specify required start-up costs (to cover, e.g. employment costs for extra technician staff and new instrumentation to enable increased sample processing) as well as ongoing costs related to the number of samples to be processed. The latter should be met through a per sample charge to users. Bidders should indicate how much they will charge per sample, but it is expected that charges will be in the

region of £50-100 per sample. Bidders should describe their existing and expected future ability to analyse carbonate chemistry on small volume samples arising from culture experiments, from which it may not be possible to take 250 mL. Expected processing time (time from receipt of samples to return of measurements) should be specified. The central service will provide users with advice on sample collection (including running a training workshop) such as how to fill the bottles, the need to add a poison, such as mercuric chloride, and also the need to measure accurately temperature, salinity, silicate and phosphate concentrations.

Other participants in the ocean acidification programme not possessing their own measurement capability will be required to include costings for their carbonate measurements using this service in their project proposals. Measurements will be made following accepted protocols and best practice and calibrated against international certified reference materials (CRMs) (see section 5 and Dickson *et al.* 2007). It is required that an intercomparison exercise be organised and undertaken in collaboration with carbonate chemists in the BIOACID programme. Applicants to provide this service should also provide a full project management plan that includes contingency plans for possible losses of key staff and/or equipment failures.

5. Programme standards and guidelines for CO_2 experiments in ocean acidification studies

a. At least two of the four parameters of the carbonate system (DIC, alkalinity, pCO_2 and *p*H) must be measured to determine the carbonate chemistry of the marine system used and these should be calibrated against certified standards or reference materials (CRMs). DIC and alkalinity are the pair most often used. *p*H is difficult to measure to sufficient accuracy at present, and only *p*H measurements accurate to 0.002 *p*H unit should be used. Use of cheap, 'off-the-shelf' *p*H sensors is strongly discouraged for most ocean acidification related purposes, because high quality results are unlikely to be obtained. Ideally pCO_2 and *p*H should not be used as a pair as they strongly co-vary .

b. Ocean acidification experiments should primarily use a broad range of realistic atmospheric CO_2 mixing ratios, spanning glacial (180 ppm), pre-industrial (280 ppm) present day (350-385 ppm) and the future (1000+ ppm).

c. Atmospheric CO_2 mixing ratios (xCO_{2atm}) of 180, 280, 350, 450, 550, 650, 750, and 1000 ppm ($\mu mol\ mol^{-1}$) are guidelines for designing ocean acidification studies.

d. For logistically limited studies, primary targets of 350 and 750 ppm should be used.

e. Values of $xCO_{2(atm)}$ exceeding realistic ranges can be useful to examine the boundaries of organism performance, but should be followed by or coupled with realistic values.

f. Key atmospheric carbon dioxide levels should be converted to corresponding values of in situ ocean carbonate parameters for specific ocean acidification studies.

g. Experimental design and key $xCO_{2(atm)}$ and *in situ* carbonate system variables should be reported to BODC and in ocean acidification publications.

h. In experiments examining combined impact of changes in temperature and ocean acidification temperature projections from IPCC (2007) or climate models should be used.

6. Data management

NERC requires that research programmes implement a data management scheme which covers practical arrangements during the programme and subsequent long-term availability of the data set. In line with the NERC data policy (www.nerc.ac.uk/research/sites/data/policy.asp), the data from the Programme will be lodged with the appropriate NERC Designated Data Centre - the British Oceanographic Data Centre (BODC). BODC is the accredited Data Archiving Centre for such data within the framework

of the Marine Environment Data and Information Network (MEDIN). BODC also has links with the international Carbon Dioxide Information and Analysis Centre (CDIAC). As the submission point for data, BODC will receive QC-ed data from Principal Investigators (PIs) and will work closely with CDIAC to ensure that *in situ* carbonate chemistry data sets will be lodged with and be available from both CDIAC and BODC. Experimental design, key $xCO_{2(atm)}$ and *in situ* carbonate system variables should be reported to BODC. Metadata forms similar to those developed by CDIAC will be used for carbonate chemistry data (http://cdiac.ornl.gov/oceans/submit.html). Metadata for carbonate chemistry should include: (1) a description of which parameters were measured and which calculated, (2) the analytical protocols, (3) the dissociation constants and (4) computer code used in calculations and (5) the *p*H scale, e.g. total or free.

NERC puts an obligation upon PIs to ensure that data management is undertaken in a suitable way. A well structured identification system is essential for data collection and sample labelling on cruises and in experiments. Principal Scientific Officers (PSOs) should provide station identifiers and "basic" oceanographic data immediately after a cruise or large experiment and should include all appropriate metadata. For cruises a copy of the Cruise Summary Report (ROSCOP form) should be provided to BODC by the PSO within one week of the end of the cruise. A copy of the full cruise report should also be sent electronically to the BODC. In order to assist the PSO and the PIs with the overall data management a BODC representative will attend the meetings before and after cruises and large experiments. BODC management of programme data will be funded centrally.

Individual proposals should briefly state data collection plans, staff responsibilities and data quality. The Science Co-ordinator and Programme Executive Board (PEB) will be responsible for agreeing the Programme's data management plan with the data centres and overseeing data management, including regular meetings with, and annual reporting by, the data centres. He/she will also negotiate a data management policy between collaborating nations, when appropriate. To raise the profile of the *UK Ocean Acidification Research Programme* and that of the funders, there will be a requirement on all scientists who use the data and/or products to acknowledge the Research Programme, NERC, Defra and DECC in all presentations, papers, publications, etc.

7. Cruise timetable

This programme is expected to require up to 5 cruises on NERC's research ships - *RRS James Cook*, *RRS Discovery* and *RRS James Clark Ross*. It is anticipated that the cruise programme would start in 2011/12, with possibly 1 to 2 cruises, with the majority of cruise activity taking place in 2012/13 and 2013/14. The outline bid workshop will be used to help co-ordinate cruise activities. The programme is also expected to utilise cruise time on ships of opportunity as required.

8. Science Plan

The *Science Plan* for the *UK Ocean Acidification Research Programme* is available as a separate document on the NERC website and should be read prior to submitting a proposal.

9. Partnerships

The *UK Ocean Acidification Research Programme* is a partnership between NERC and the UK Government Departments Defra and DECC. The Government departments' marine laboratories will be eligible for funding and collaboration between the different science communities is encouraged. Other partnerships will be sought providing both direct funding

and in kind contributions. Ocean Acidification is a *Living With Environmental Change* (LWEC) accredited programme.

10. International collaboration

Collaborations between UK scientists, research institutions, disciplines and other national and European programmes are strongly encouraged, where appropriate, in order to deliver more effectively the UK programme's *Science Deliverables* and *Objectives*. In particular collaboration should be sought with the three year (2009-2012), German programme ***Bio****logical Impacts of Ocean* ***Acid****ification* (BIOACID) and the four year (2008-2013), EU Framework 7 programme's ***E****uropean* ***P****roject on* ***Oc****ean* ***A****cidification* (EPOCA) and *Marine* ***E****cosystem* ***E****volution in a* ***C****hanging* ***E****nvironment* (MEECE).

BIOACID is the 9.25M€ German ocean acidification programme funded by the Bundesministerium für Bildung und Forschung (Federal Ministry for Education and Research) bringing 21 leading German partners together and looking at all aspects of the biological impacts of ocean acidification, from underlying mechanisms of responses, to adaptations and the consequences for marine ecosystems and biogeochemical cycles. To cement the close collaboration with BIOACID, its Science Co-ordinator, Ulf Riebesell, was invited to be a member of the Writing Team for the *UK Ocean Acidification Research Programme*. BIOACID Phase II will start in 3 years time and it is anticipated that further alignment and collaboration between the German and UK programmes will occur then.

EPOCA is a 6.5M€ EU FP7 Integrated Project bringing together more than 100 researchers from 27 institutes and 9 European countries to investigate chemical, biological and biogeochemical impacts across time and space and to integrate them into ecosystem models to access risk and uncertainties.

MEECE is a 6.5M€ EU FP7 Integrated Project made up of 21 partners from across Europe. The project aims to increase ecosystem modelling predictive capacities of both natural and human-induced climate pressures impacts, including ocean acidification, on the structure and function of marine ecosystems.

To help facilitate collaboration Annexes 1 and 2 have the science summaries, themes and/or work packages of these programmes and the contact details of the lead scientists. The Science Co-ordinators of all three programmes have welcomed collaboration with the *UK Ocean Acidification Research Programme*. Collaboration can take the form of exchange visits to work together in the laboratory, on mesocosm experiments and at sea on cruises as well as student costs for a period of exchange. In addition, BIOACID and EPOCA have agreed to share annual meetings, workshops and intercalibration exercises for carbonate chemistry with the UK programme. It is recommended that the Programme Advisory Group (PAG) includes representatives from one of more of these international programmes. It is further anticipated that the Science Co-ordinator for the UK Programme will play a key role in encouraging and facilitating collaboration as these programmes develop as well as keep the Programme Executive Board (PEB) fully informed of new opportunities.

As the issue of ocean acidification emerges there is every likelihood that other national and international programmes will arise with opportunities for collaboration. For instance, in the USA the "Ocean Acidification Research and Monitoring Act" establishes a new federal program ($100 million over five years) within the National Oceanic and Atmospheric Administration (NOAA) to conduct research and public outreach on ocean acidification. It is also anticipated that there will be continued interest in ocean acidification from a wide range

of funders and stakeholders. For example, IPCC included ocean acidification as a new finding in its 4th Assessment Report on Climate Change and it is expected that ocean acidification will play a more substantial role in the 5th Assessment Report.

11. Knowledge Exchange

The main aim for Knowledge Exchange (KE) in the *UK Ocean Acidification Research Programme* will be to facilitate the communication and application of the science delivered from this programme to policy makers. This will be achieved through various activities including policy placements within Government Departments, annual input to the MCCIP and production of policy relevant information such as updates, briefings and summaries. Other key KE activities will include:

- Engagement with the relevant reference user groups of key stakeholders. This will be used as a mechanism to ensure the relevance, user-friendliness and outreach of the research delivered from this programme throughout its lifetime.
- Development of a media policy, press releases and media activities.

A Knowledge Exchange plan will be developed by the KE Co-ordinator (Section 12), who will work closely with Defra and DECC to ensure the successful implementation of activities.

12. Programme Management

12.1 Programme Executive Board (PEB)

The *UK Ocean Acidification Research Programme* will be managed by NERC Swindon Office in close co-ordination with Defra (Marine Strategy and Evidence Sub programme), and DECC. The PEB will be chaired by NERC and the membership will include representatives from Defra and DECC.

12.2 Programme Advisory Group (PAG)

A Programme Advisory Group (PAG) will advise the PEB on the delivery of the *UK Ocean Acidification Research Programme.* The PAG will consist of national and international experts, including representatives of all funders, be chaired by a scientist familiar with the *UK Ocean Acidification Research Programme* and the operations of the funders. The PAG will work closely with the Science Co-ordinator, the Knowledge Exchange Co-ordinator and the Programme Administrator. The PAG shall be appointed by NERC by June 2009.

12.3 Grant Moderating Panel (GMP)

A Grant Moderating Panel (GMP) will have the responsibility of assessing research proposals both in terms of quality of proposed science and their ability to deliver the requirements of the *UK Ocean Acidification Research Programme*. It will consist of national and international experts in the field of ocean acidification and include a representative from the co-funders and at least one member of the NERC Peer Review College. These assessments will inform the PEB's decisions on the award of funding to deliver the programmes objectives.

12.4 Programme Management Team (PMT)

There will be three important processes involved in programme management: that of science co-ordination, knowledge exchange co-ordination and programme administration, and these roles will work closely together to provide effective management of the programme.

A **Programme Administrator** will be based at the NERC Swindon Office and administer the grants, assist with organising the workshops and meetings, organise and take actions at meetings of the PEB and PAG and other administrative aspects of the programme.

The **Science Co-ordinator** will be a part time role (at the level of 0.5 FTE) and responsible for the day-to-day management and coordination of the programme. They will continue to

develop the *Implementation Plan* and *Data Management Plan* and ensure that the open call activities deliver the *Science Deliverables*. The Science Co-ordinator, with the assistance of the Programme Administrator, will administer the awards process, feeding back information to unsuccessful candidates and, where necessary, negotiating modifications to the work plan and/or finances of successful applications. In addition, the Science Co-ordinator will maintain an overview of the scientific progress made against the seven *Science Deliverables* and work to ensure co-ordination between the different science components of the *UK Ocean Acidification Research Programme*. The Science Co-ordinator will liaise with all the *UK Ocean Acidification Research Programme* participants, facilitate the development of the ocean acidification community, and develop the links between this programme and international collaborators. They will also be responsible for the monitoring and reporting on behalf of the whole programme, including annual reporting and the completion of output performance measures (OPMs).

The **Knowledge Exchange Co-ordinator** will be a part time role (at the level of 0.5 FTE) and will be responsible for the development and implementation of the Knowledge Exchange Plan that will deliver programme *Objective c*. They will collaborate with all scientists in the programme in the co-ordination of KE, and liaise closely with Defra and DECC to ensure the successful delivery of the KE plan.

The Programme Management Team (PMT) will be responsible for the organisation of workshops and annual meetings in collaboration with BIOACID and EPOCA to maintain close interaction with these programmes.

13. Programme timetable and open call

A Writing Team (WT) was appointed in December 2008 to draft the Research Programme's Science and Implementation Plans. These were submitted for approval and publication by NERC, Defra and DECC in April 2009. An open 'Research Programme' call will be made for proposals to deliver the programme's *Science Deliverables 1-6* and achieve the programme *Objectives a and b*. The primary mechanism for this will be an announcement of opportunity for outline bids in May 2009 with the following timetable:

June 2009	Announcement of opportunity
Mid-July 2009	Outline bid deadline
End-July 2009	Outline bid decision
September 2009	1 day workshop for successful applicants
End 2009	Full bid deadline
Beginning 2010	Panel meeting

The PAG and independent experts will evaluate these and a subset will be invited to submit full proposals. A workshop for those invited to submit full proposals will be held directly after this decision has been made. The full proposals will be internationally peer reviewed and final funding recommendations made by a Grant Moderating Panel (GMP). GMP members directly involved in proposals being considered will be excluded from those parts of the GMP discussions that affect their proposal to avoid vested interest issues. It is anticipated that funded proposals would start in early 2010.

Proposals submitted to the open call will be required to address both the *Science Deliverables* and detail how they will contribute to the *UK Ocean Acidification Research Programme's Objectives* (section 3). International collaborations, particularly with the German BIOACID and EU EPOCA and MEECE programmes, is strongly encouraged where appropriate.

International collaborators will benefit from access to data, but will not receive Programme funding. Activities must:

- comply with standard NERC and UK Government reporting requirements.
- ensure completion of a two page research and development (R & D) document.
- contribute to the *Knowledge Exchange* activities.
- comply with the programme's media policy.
- use the programme's carbonate chemistry analytical service (section 4 *Science Deliverable 7*) where not possessing their own high quality capability.
- comply with the programme's data management policy.
- identify collaboration with participants within the *UK Ocean Acidification Research Programme* and other national and international programmes when appropriate.

It is anticipated that research grants will, where appropriate, have Terms and Conditions that include milestones and deliverables to ensure that this Research Programme effectively delivers the seven *Science Deliverables*. Funded proposals will usually be up to 3 years in duration unless cases for different durations are given and accepted by the GMP.

The Science Co-ordinator and Knowledge Exchange Co-ordinator will be appointed towards the end of 2009.

14. Referemces

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15. Glossary

BAS = British Antarctic Survey
BGS = British Geological Survey
BIO = Bedford Institute of Oceanography, Canada
BIOACID = Biological Impacts of Ocean ACIDification
BODC = British Oceanographic Data Centre
CARBOOCEAN = Marine Carbon Sources and Sinks Assessment (EU Project)
CDIAC = Carbon Dioxide Information and Analysis Centre
CRM = Certified Reference Material

DECC = Department of Energy and Climate Change
Defra = Department for Environment, Food and Rural Affairs
DFO = Fisheries and Oceans Canada
DIC = Dissolved Inorganic Carbon
EPOCA = European Project on Ocean Acidification
EU = European Union
FTE = Full Time Equivalent
GLODAP = GLobal Oceans Data Analysis Project
GMP = Grant Moderating Panel
IPCC = Intergovernmental Panel on Climate Change
LWEC = Living With Environmental Change
MCCIP = Marine Climate Change Impacts Partnership
MEDIN = Marine Environment Date and Information Partnership
MEECE = Marine Ecosystem Evolution in a Changing Environment (EU Project)
NERC = Natural Environment Research Council
NHM = Natural History Museum
NMFS = National Marine Fisheries Service
NOAA = National Oceanic and Atmospheric Administration
OA = Ocean Acidification
Oceans 2025 = NERC Marine Centres Research Programme
OPM = Output and Performance Measures
PAG = Programme Advisory Group
PEB = Programme Executive Board
PI = Principal Investigator
PIC = Particulate Inorganic Carbon
PMT = Programme Management Team
POC = Particulate Organic Carbon
QC = Quality Control
RECLAIM = Resolving Climatic Impacts on Fish Stocks (EU Project)
SISB = Science and Innovation Strategy Board
UNCOVER = Understanding the Mechanisms of Stock Recovery (EU Project)
WT = Writing Team

16. Annex 1: BIOACID programme and contacts

Please find on the NERC website as a separate document.

17. Annex 2: EPOCA and MEECE Summaries and contacts

The ocean helps moderate climate change thanks to its considerable capacity to store CO_2, through the combined actions of ocean physics, chemistry, and biology. This storage limits the amount of human-released CO_2 remaining in the atmosphere. As CO_2 reacts with seawater, it generates dramatic changes in carbonate chemistry, including decreases in *p*H and carbonate ions and an increase in bicarbonate ions. The consequences of this overall process, known as "ocean acidification", are raising concerns for its biological, ecological, biogeochemical, and societal implications. The overall goal of the *European Project on Ocean Acidification* (EPOCA; epoca-project.eu) is to fill numerous gaps in the understanding of the consequences of ocean acidification. The EU funded project started in May 2008 and runs for 4 years. The Coordinator is Jean-Pierre Gattuso (gattuso@obs-vlfr.fr) and the Project Manager is Lina Hansson (hansson@obs-vlfr.fr), CNRS - Laboratoire d'Océanographie de Villefranche (France). The research interests of EPOCA are divided into four themes, each with a leader:

First, EPOCA aims to document the changes in ocean chemistry and geographical distribution of marine organisms across space and time. Paleo-reconstruction methods are used on several archives, including foraminifera and deep-sea corals, to determine the past variability in ocean chemistry (carbonate, nutrients and trace metals) and to tie these to present-day chemical and biological observations. Theme Leader: Jella Bijma (Jelle.Bijma@awi.de).

Second, EPOCA devotes much effort to quantifying the impact of ocean acidification on marine organisms and ecosystems. Key climate-relevant biogeochemical processes such as calcification, primary production and nitrogen fixation are investigated using a large array of techniques, ranging from molecular tools to physiological and ecological approaches. Perturbation experiments are carried out both in the laboratory and in the field. Key organisms are selected on the basis of their ecological, biogeochemical or socio-economic importance. Theme Leader: Ulf Riebesell (uriebesell@ifm-geomar.de).

Third, the modelling component of EPOCA integrates the chemical, biological and biogeochemical impacts of ocean acidification into biogeochemical, sediment and coupled climate carbon cycle models. Special attention is paid to feedbacks of physiological changes on the carbon, nitrogen, sulphur and iron cycles and in turn how these changes will affect and be affected by future climate change. Theme Leader: Marion Gehlen (Marion.Gehlen@cea.fr).

Finally, EPOCA assesses uncertainties, risks and thresholds ("tipping points") related to ocean acidification at molecular, cellular, organismal, local and global scales. It also assesses pathways of CO_2 emissions required to avoid the identified thresholds and describe the state

change if these emissions are exceeded and the subsequent risk to the marine environment and Earth system. Theme Leader: Carol Turley (ct@pml.ac.uk)

MEECE is a European FP7 Integrated Project which aims to increase ecosystem modelling predictive capacities. Both natural and human-induced climate pressures have an impact on the structure and function of marine ecosystems. Using a combination of data synthesis, numerical simulation and targeted experiments MEECE intends to boost our knowledge and develop the predictive capabilities needed to learn about the response of marine ecosystems.

MEECE will also develop methods to integrate the dynamic response of marine ecosystems to the combined effects of various anthropogenic and natural drivers in order to provide decision making tools to support the EC Marine Strategy, EC Maritime Policy and the EC Common Fisheries Policy.

The MEECE Project Coordinator is Icarus Allen (JIA@pml.ac.uk.).There are 6 main workpackages (WP) within the MEECE project. Below are the WP titles and leaders but please see the MEECE web site: http://www.meece.eu/ for individual descriptions and further details:

WP1: Driver Parameterisations and model scenarios - Richard Bellerby and Sergej Olenin
WP2: Advanced modelling - Mike St John and Steve Mackinson
WP3: Ecosystem response to climate change and acidification - Xabier Irigoien and Jason Holt
WP4: Ecosystem response to direct anthropogenic drivers - Marco Zavatarelli and Yunne Shin
WP5: Implications for resource management - GerJan Piet and Fritz Köster
WP6: Knowledge Transfer and Outreach - Manuel Barange and Jessica Heard