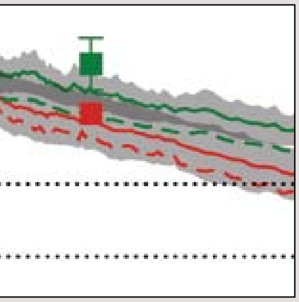
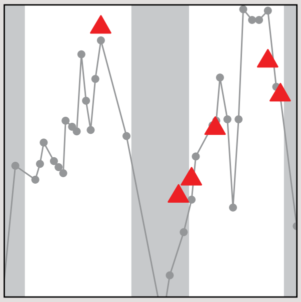
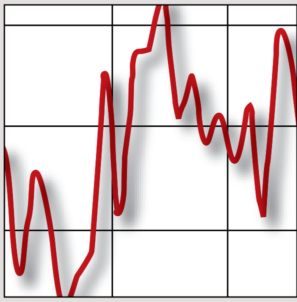
BY JEAN-PIERRE GATTUSO, LINA HANSSON, AND THE EPOCA CONSORTIUM[1]

European Project on Ocean Acidification (EPOCA)

OBJECTIVES, PRODUCTS, AND SCIENTIFIC HIGHLIGHTS







ABSTRACT. The European Project on Ocean Acidification (EPOCA) is Europe's first large-scale research initiative devoted to studying the impacts and consequences of ocean acidification. More than 100 scientists from 27 institutes and nine countries bring their expertise to the project, resulting in a multidisciplinary and versatile consortium. The project is funded for four years (2008 to 2012) by the European Commission within its Seventh Framework Programme. This article describes EPOCA and explains its different aspects, objectives, and products. Following a general introduction, six boxes highlight outcomes, techniques, and scientific results from each of the project's core themes.

[1] Table 1 contains a complete list of EPOCA participants.

INTRODUCTION

Seawater carbonate chemistry is currently undergoing modifications at a rate of change that has not been observed throughout Earth history (Caldeira and Wickett, 2003). The world ocean absorbs anthropogenic carbon dioxide (CO_2) at a rate of approximately 24 million tons per day, provoking chemical perturbations that ultimately result in a reduction in pH and carbonate ion concentration. These reductions lead to a drop in calcium carbonate saturation state, making seawater less favorable to precipitation of calcareous shells and skeletons and more favorable to their dissolution.

Whereas the chemical consequences of ocean acidification are perfectly foreseeable, the potential responses of organisms and ecosystems to the phenomenon are still highly speculative, due to the scarce and sometimes conflicting data available. Throughout the very brief history of ocean acidification research, attention has often been devoted to the behavior of calcifying organisms in a high-CO_2 ocean, given their dependence on carbonate ions as building blocks for calcium carbonate structures such as shells and skeletons. Other processes such as nutrient uptake, reproduction, acid-base regulation, nitrogen fixation, and primary production are also likely to be affected, positively or negatively, by the decline in pH and the increase in CO_2.

Ocean acidification has for many years stood in the shadow of its "big brother," climate change; both originate from the same cause: the release of CO_2 into the atmosphere by human activities. The effects of ocean acidification might be as dramatic as those of global warming, providing another reason to drastically cut CO_2 emissions. Emerging projects in Europe and the United States show the increased concern that ocean acidification currently generates. The scientific results, or rather the lack thereof, are a cause for worry, and more research is needed to fill the gaps in our understanding of ocean acidification and its impacts on marine flora and fauna.

Several recent developments, including the Monaco declaration released on January 29, 2009, in which 155 scientists urge policymakers to take immediate action, as well as the decision of the US Environmental Protection Agency to classify CO_2 as a pollutant, add to the increased attention presently focused on this relatively young research field.

The European Project on Ocean Acidification (EPOCA) is Europe's answer to increasing concern about an ocean rich in CO_2. EPOCA was launched in May 2008 with the overall goal of furthering our understanding of the biological, ecological, biogeochemical, and societal implications of ocean acidification. The project brings together over 100 scientists from 27 institutes and nine European countries (Table 1).

OBJECTIVES

With the goal of advancing our current knowledge of ocean acidification and its implications, EPOCA's research efforts are organized around four core themes.

Theme 1: Changes in Ocean Chemistry and Biogeography

What are the past and present fluctuations in carbonate chemistry and biogeography of marine key species? An important part of EPOCA focuses on such spatial and temporal variations. EPOCA scientists study past variability in ocean chemistry via paleoreconstruction methods that draw on archives such as those devoted to cold-water corals and foraminifera (see Box 1). Continuous sampling and measurements at time-series stations and along transects, mostly in northern latitudes such as the Arctic Ocean and the North Atlantic, constitute the observational component of EPOCA.

Theme 2: Biological responses

How will marine organisms and ecosystems react in response to ocean acidification? EPOCA's largest research theme is devoted to the impacts of ocean acidification on marine biota, from planktonic species to higher trophic levels. Laboratory and mesocosm CO_2 perturbation experiments, combined with experimental approaches ranging from molecular to ecosystem scale, are used to study key organisms and physiological processes in an attempt to quantify the biological response and assess acclimation and adaptation possibilities.

Theme 3: Biogeochemical impacts and feedbacks

To what extent will ocean acidification alter ocean carbonate chemistry, biogeochemistry, and marine ecosystems over the next 200 years, and what feedbacks will these changes generate to the climate system? Results from Themes 1 and 2 are incorporated into biogeochemical, sediment, and coupled ocean-climate models to project future variability in carbonate chemistry, responses to ocean acidification from the Earth system, and feedbacks. Special attention is paid to the potential feedbacks of the biological changes in the carbon, nitrogen, sulfur, and iron cycles.

Theme 4: Synthesis, dissemination, and outreach

What conclusions can be drawn from combining the results from Themes 1, 2, and 3? Uncertainties, risks and potentially critical thresholds or "tipping points"[2] associated with ocean acidification are communicated to policymakers and the general public in a comprehensible format and language. The EPOCA strategy aims to contribute high-quality science directly to expert groups and committees through the formation of the EPOCA Reference User Group (RUG) of stakeholders. RUG advises EPOCA on the format and the nature of key messages arising from the project and on the dissemination procedures.

Information exchange among the different themes moves in both directions (Figure 1). For example, Theme 3 exploits information from Themes 1 and 2 to predict future changes in ocean biogeochemistry and ecosystems, but results from Theme 3 will also be used by Themes 1 and 2 to provide critical information on the expected temporal and spatial changes of ocean acidification and thus enable meaningful experimental designs.

[2] A tipping point is the critical threshold in an evolving situation that, when crossed, leads to a new and irreversible state.

Table 1. List of EPOCA partner institutions with their acronyms and countries

Partner Number	Partner
1	National Center for Scientific Research (CNRS, France)
1.1	Laboratoire d'Océanographie de Villefranche (LOV, France)
1.2	Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement (CEREGE, France)
1.3	Station Biologique de Roscoff (SBR, France)
2	University of Bergen (UiB, Norway)
3	Leibniz-Institute of Marine Sciences at Kiel University (IFM-GEOMAR, Germany)
4	Natural Environment Research Council (NERC, UK)
5	*Alfred Wegener Institute* for Polar and Marine Research (AWI, Germany)
6	The Chancellor, Masters and Scholars of the University of Cambridge of the Old Schools (UCAM, UK)
7	French Atomic Energy Commission, Laboratoire des Sciences du Climat et l'Environnement (CEA, LSCE, France)
8	Plymouth Marine Laboratory (PML, UK)
9	Scottish Association for Marine Science (SAMS, UK)
10	Max Planck Society for the Advancement of Science (MPG, Germany)
11	Marine Biological Association (MBA, UK)
12	University of Gothenburg (UGOT, Sweden)
13	Royal Netherlands Institute for Sea Research (NIOZ, The Netherlands)
14	University of Utrecht (UU, The Netherlands)
15	Royal Netherlands Academy of Arts and Sciences (KNAW, The Netherlands)
16	Sir Alister Hardy Foundation for Ocean Science (SAHFOS, UK)
17	GKSS Research Centre (GKSS, Germany)
18	University of Bern (Ubern, Switzerland)
19	Université Libre de Bruxelles (ULB, Belgium)
20	Philippe Saugier International Educational Projects (PSIEP, France)
21	VU University (VUA, The Netherlands)
22	Swiss Federal Institute of Technology Zurich (ETH ZURICH, Switzerland)
23	Hafrannsóknastofnunin - Marine Research Institute (HAFRO-MRI, Iceland)
24	University of Southampton (SOTON-SOES, UK)
25	University of Plymouth (UoP, UK)
26	Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO)
27	University of Bristol (UNIVBRIS, UK)

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BOX 1. PAST CHANGES IN OCEAN PH

By Jelle Bijma and Harry Elderfield

Determining how past changes in ocean acidity have affected species and ecosystems provides an important framework for assessing ocean acidification. For example, have historical changes in carbonate ion concentration and pH since industrialization already had discernible impacts on the calcification of marine organisms? On longer time scales, can we use information such as glacial to interglacial changes in atmospheric CO_2 to examine whether marine calcifying organisms have responded to such changes? A reliable proxy for past ocean pH is required to answer such questions. Such a proxy is based on the seawater speciation of boron.

Boron (B), a conservative element in seawater, exists primarily as a mixture of two species: boric acid ($B(OH)_3$) and borate ($B(OH)_4^-$), with the percentages of each dependent on pH (Figure B1a). Boron has two isotopes, ^{11}B and ^{10}B, and the isotopic composition ($\delta^{11}B$, normalized to a standard) of the two boron species in seawater is also controlled by pH (Figure B1b). The B isotopic composition of marine biogenic carbonates reflects the isotopic composition of the $B(OH)_4^-$ species at the pH at which they were formed (Figure B1b). This observation suggests that only the borate species is incorporated from seawater into $CaCO_3$. Hence, if pH determines the isotopic composition of borate and if it is the only species incorporated into calcium carbonates (Figure B1b.), then both the $\delta^{11}B$ and the B content of the carbonates can be used to reconstruct pH.

A proof-of-concept study (Yu et al., 2007) compared estimates of pH, using the B isotope and content approaches, with atmospheric CO_2 from ice core data over four glacial-interglacial cycles. Results (Figure B2) are very promising and provide the basis for applications to investigate past periods of ocean acidification.

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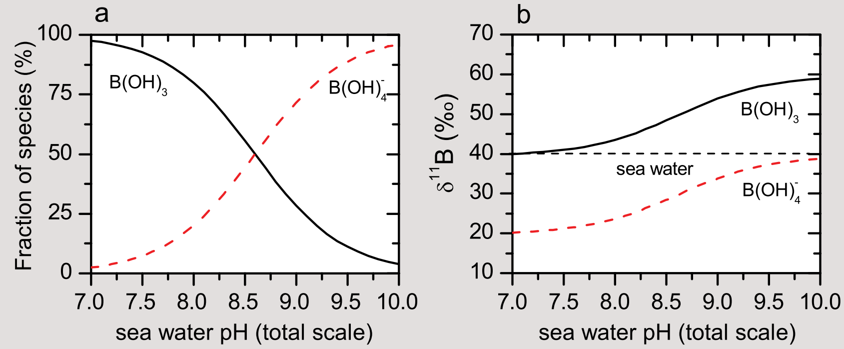

Figure B1. (a) Calculated relative percentages for the two aqueous species of boron, boric acid ($B(OH)_3$) and borate ($B(OH)_4^-$) plotted against seawater pH. (b) Boron isotopic composition of the two species, assuming a fractionation factor (the ratio of the heavy isotope [^{11}B] to that of the light isotope [^{10}B]) of 0.981. The boron isotopic composition of seawater is 39.6 per mil (this is the parts per thousand deviation of the $^{11}B/^{10}B$ ratio from a standard).

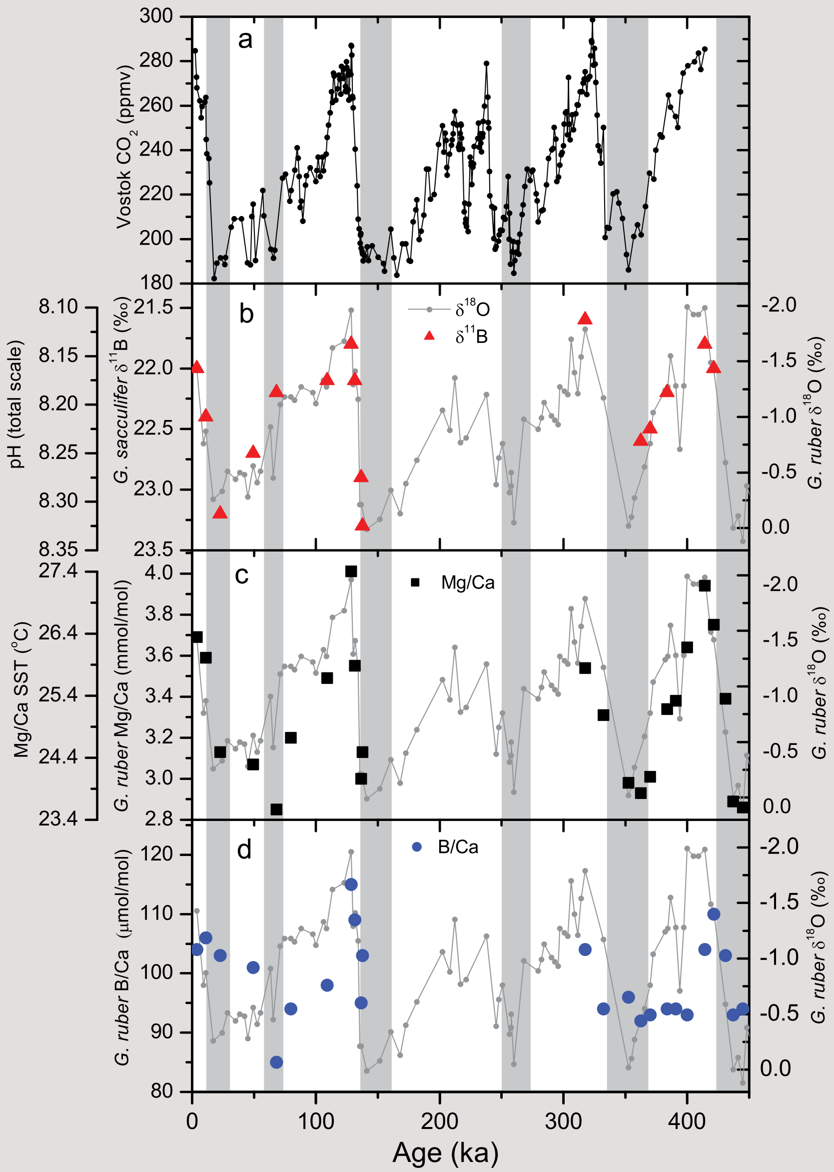

Figure B2. Paleoclimate records for the past 450 kyr (Yu et al., 2007). (a) Atmospheric CO_2 from Vostok ice core and records from an Atlantic Ocean sediment core showing oxygen isotope composition of foraminifera and (b) B isotopes, (c) Mg/Ca, and (d) B/Ca of foraminifera.

CROSSCUTTING ACTIVITIES

Data Management

The EPOCA Data Management team collects, quality controls, and archives data to facilitate a consistent information exchange. Two major types of data are handled: (1) direct measurements from Themes 1 and 2 (e.g., proxy data, water column data, and data from process studies, mesocosms, and laboratory experiments) and (2) model outputs from Themes 2 and 3 (e.g., four-dimensional velocity and tracer fields, material fluxes, various biogeochemical and ecological parameter estimates). The EPOCA database is available at: http://www.epoca-project.eu/index.php/What-do-we-do/Science/Data/Data-search.html.

Training and Education

In order to share recent findings on ocean acidification with early career scientists, set the stage for future research, and facilitate collaboration among disciplines, EPOCA has designed a series of training activities. EPOCA, the European project CARBOOCEAN, and the International Oceanographic Commission of UNESCO (IOC-UNESCO) organized a training workshop on the fundamentals of carbon biogeochemistry that brought together nearly 50 participants in Bergen in early February 2009. A workshop on the basics of paleoreconstruction methods used in ocean acidification research took place in Cambridge in September 2009. EPOCA also cosponsored, with the US Ocean and Carbon Biogeochemistry (OCB) program, a training course that took place in Woods Hole in November 2009. Other training workshops for PhD students and postdocs are planned; the next one, in Kiel in March 2010, will consider CO_2 perturbation experiments. The workshops are open to non-EPOCA scientists whenever possible.

PhD students and postdocs are also invited to get involved in EPOCA school projects to increase their skill in communicating with nonscientific audiences. Although global warming and climate change are well-known concepts among young people, ocean acidification is new to most of them, and an important aspect of EPOCA is to share knowledge of ocean acidification with schools.

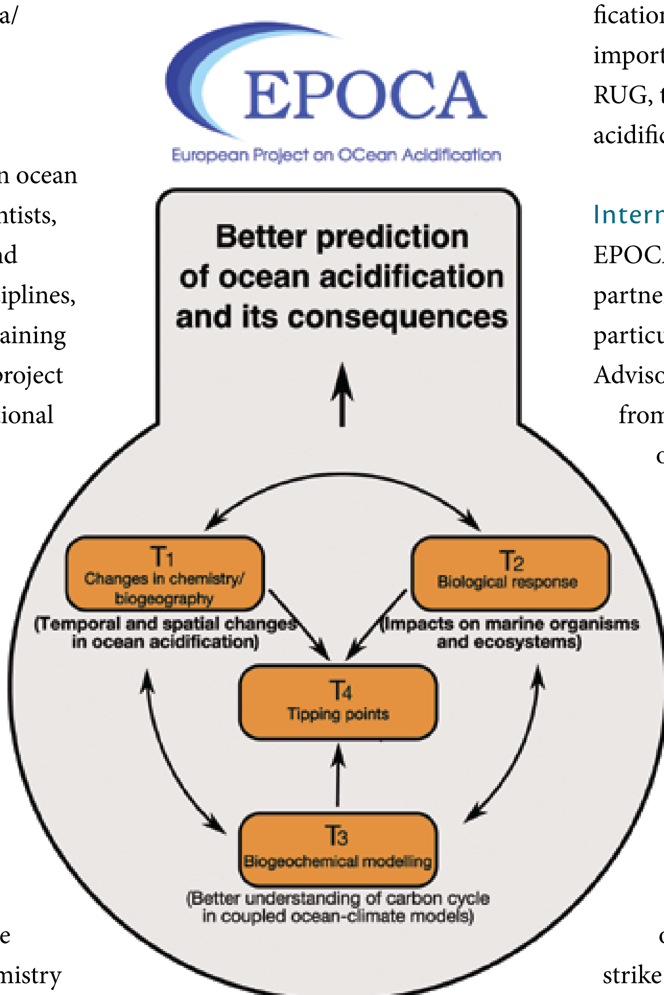

Figure. 1. The four themes of EPOCA and their interaction.

EPOCA has joined the CarboSchools initiative, which implements educational projects with strong scientist–teacher–pupil interaction. For more information, see www.carboschools.org.

Scientific Dissemination and Outreach

EPOCA is in active contact with policymakers, business leaders, non-EPOCA scientists, and the general public to inform them about project findings. Several tools, such as the EPOCA Web site (http://www.epoca-project.eu/), leaflets, and a blog dedicated to ocean acidification, are used to share results from the project and research on ocean acidification in general. EPOCA uses another important communication channel, RUG, to get out the message on ocean acidification to a broader audience.

International Collaboration

EPOCA cooperates with international partners on ocean acidification. In particular, its International Scientific Advisory Panel, which includes members from the United States and Korea, and one of the EPOCA partners (the intergovernmental organization IOC-UNESCO) ensure that ocean acidification research being carried out through EPOCA is coordinated with the research activities of non-EU scientists.

EPOCA Svalbard Campaigns 2009 and 2010

EPOCA focuses on areas where ocean acidification is expected to strike first, such as the Arctic Ocean and the North Atlantic, where water temperatures are low, promoting CO_2

BOX 2. EUROPEAN TIME SERIES OF CALCAREOUS ORGANISMS AND CARBONATE CHEMISTRY

By Peter Burkill, Toby Tyrrell, and Martin Edwards

Temperature, light, and nutrients are normally considered key variables in structuring marine ecosystems. However, changes in ambient CO_2 levels in the atmosphere and the surface ocean will also influence plankton. Rising CO_2 is causing the ocean's acidity to increase. Ocean acidification is likely to affect the process of calcification, and calcified plankton such as coccolithophores, foraminifera, and pelagic mollusks may be particularly vulnerable. Quite apart from the impact on the organisms themselves, any changes in the calcified taxa may change the ocean's ability to act as a global carbon sink and may thus act as a feedback to the rate and scale of climate warming.

Despite such concepts, data from the Continuous Plankton Recorder (CPR) survey of the North Atlantic suggest that certain calcareous taxa are actually increasing in abundance, a trend associated with climate shifts in Northern Hemisphere temperature. As an example, planktonic foraminifera are increasing in abundance across the North Atlantic (Figure B3). However, observations from the Southern Ocean suggest that modern shell weights of foraminifera have decreased compared with much older sediment core records, with acidification being implicated as the driver (Moy et al., 2009). It is not yet known how much of an effect acidification will have on the biology of the oceans in the twenty-first century, whether climate warming or acidification will have the greatest impact, and whether or not species will be able to cope with the effects of acidification through adaptation. The CPR survey is providing a critical baseline (both in space and time) and is currently monitoring these vulnerable organisms in case they begin to show negative effects due to acidification in the future.

European groups have already undertaken much work on monitoring pCO_2 in surface seawater, calculating variation through time in net CO_2 fluxes into the ocean, in particular across the North Atlantic Ocean (e.g., Schuster and Watson, 2007). An eight-year time-series of pH at the ESTOC (European Station for Time Series in the Ocean) site on the eastern side of the North Atlantic subtropical gyre has been important in demonstrating the reality of ocean acidification (Santana-Casiano et al., 2007), as have 24 years of measurements near Iceland (Olafsson et al., 2009). Other work has measured two or more parameters of the carbonate system on a repeated basis, allowing calculation of the whole carbonate system, including carbonate ion and $CaCO_3$ saturation states. Such work has yielded an improved understanding of the seasonal cycles of carbonate parameters; for instance, repeat sampling at Ocean Weather Station M in the Norwegian Sea, combined with modeling, reveals that biology strongly drives the seasonal cycles of carbonate ion and saturation

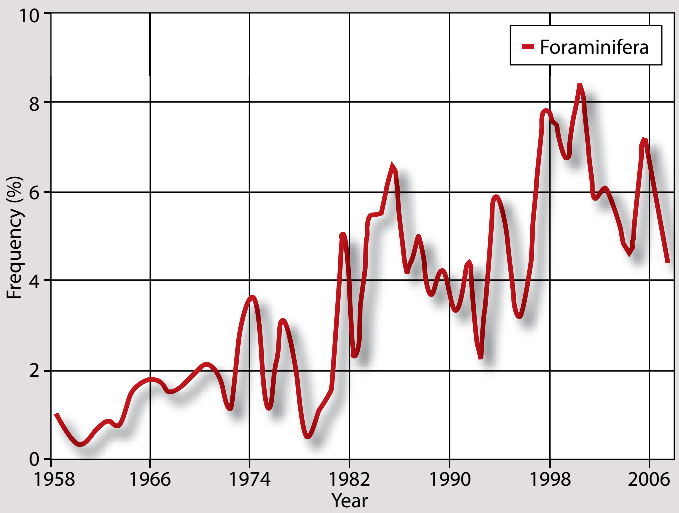

Figure B3. Percent frequency of foraminifera recorded on Continuous Plankton Recorder (CPR) survey samples. Pelagic foraminifera have become more common in the past 50 years in the North Atlantic, according to this study. *Data provided by Sir Alistair Hardy Foundation for Ocean Science*

(Ω) at this location, and that it drives them to higher values in summer than in winter (Findlay et al., 2008), leading to the prediction that the first occurrence of undersaturation ($\Omega < 1$) at different locations will take place in winter. Monitoring of seawater carbonate chemistry has also revealed considerable year-to-year variations in the surface carbonate chemistry of the North Atlantic (Corbière et al., 2007), as well as naturally low $CaCO_3$ saturation states ($\Omega \leq 1$) in wintertime in the Baltic Sea (Tyrrell et al., 2008).

Ongoing work aims to improve our knowledge of geographical and temporal variations in carbonate chemistry in European seas and adjacent oceans, and there are continuing measurements of the progression of ocean acidification at different locations. Further insights will come from simultaneous monitoring of both carbonate chemistry and calcareous organisms on the same platforms.

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BOX 3. OCEAN ACIDIFICATION EFFECTS ON KEY ECOLOGICAL INTERACTIONS AMONG SPECIES

By Steve Widdicombe

Ocean acidification has the potential to affect marine organisms in a variety of ways, from the movement of material within individual cells to the structure and function of whole communities (Widdicombe and Spicer, 2008). So far, many of the laboratory-based experiments conducted have focused on the responses of important physiological processes to increasing levels of CO_2, for example, calcification (e.g. Gazeau et al., 2007; Comeau et al., 2009), acid-base balance (e.g., Miles et al., 2007; Spicer et al. 2007), metabolic rate (e.g., Gutowska et al., 2008), protein synthesis (e.g., Michaelidis et al., 2005), and immune system function (e.g., Bibby et al., 2008). These extremely successful studies have already provided huge insight into the underlying mechanisms that dictate an individual organism's response to acidification. This understanding will be further advanced by the continuation of such experiments within the EPOCA program, with particular attention paid to the interaction between ocean acidification and other environmental stressors, such as increasing temperature.

The continuation of such studies is important because the physiological responses of individuals to specific environmental drivers will determine which organisms have the potential to tolerate changing conditions and will ultimately restrain the pool of potentially available species from which communities will be assembled. However, the actual composition and diversity of any resulting community will be controlled largely by the many biological interactions (e.g., competition, predation, facilitation) that occur among individuals and species in the natural environment. Consequently, species that are shown to be susceptible to ocean acidification in laboratory studies can actually appear to benefit from exposure to low pH when the exposure takes place in a multispecies environment (e.g., Wootton et al. 2008). Caution must therefore be taken when scaling up the results of tightly controlled, single-species experiments to predict the large-scale changes in composition and diversity of natural communities likely to result from ocean acidification. Unfortunately, mesocosm and field studies that look specifically at the responses of intact samples of a natural community or target biological interactions between organisms are currently few and far between.

Figure B4. The predatory green shore crab *Carcinus meanus* with its prey, the periwinkle *Littorina littorea. Photo courtesy of Sarah Dashfield, Plymouth Marine Laboratory*

To highlight the importance of mesocosm studies and demonstrate the extent to which ocean acidification can affect key biological interactions, we discuss a recent study that examined the impact of elevated levels of CO_2 on the relationship between a marine predator and its prey (Bibby et al., 2007). The intertidal periwinkle *Littorina littorea* is a common inhabitant of temperate rocky shores where it is heavily preyed upon by the green shore crab *Carcinus meanus* (Figure B4). As a way to reduce its vulnerability to predation, *L. littorea* can actively thicken its shell when it detects the chemicals naturally excreted by the crabs. Consequently, if the snails are living in an environment full of predators, they can reinforce their calcified defenses. Such induced defenses are common in marine organisms and allow prey species to vary their defensive structures and behaviors, depending on the level of predation risk in their environment (Tollrian and Harvell, 1999).

Bibby et al. (2007) demonstrate that under mesocosm conditions, *Littorina littorea* exhibited a normal induced defense response and snails exposed for 15 days to the crab chemicals produced shells that were 30% thicker than those that were not exposed to the chemical cue. However, this response was disrupted at reduced levels of seawater pH, and no shell thickening was observed. This lack of induced response was accompanied by a marked depression in metabolic rate (hypometabolism) only under the joint stress of high predation risk and reduced pH. However, snails in this experiment apparently compensated for a lack of morphological defense by increasing their avoidance behavior, which, in turn, could affect their interactions with other organisms, including reducing the amount of time they spend feeding. These initial findings highlight the necessity of future studies that explicitly explore the impact of ocean acidification on the key biological interactions that bind ecosystems together.

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BOX 4. EXPERIMENTAL APPROACHES IN OCEAN ACIDIFICATION RESEARCH

By Ulf Riebesell

Progress in our ability to make reliable predictions of the impacts of ocean acidification on marine biota critically depends on our capability to conduct experiments that cover the relevant temporal and spatial scales. One of the greatest challenges in this context will be scaling up biotic responses at the cellular and organismal level to the ecosystem level, and their parameterization in regional ecosystem and global biogeochemical models. EPOCA employs a suite of experimental approaches to assess marine biota's ocean acidification sensitivities, ranging from single species culture experiments, to field surveys of the distribution of potentially sensitive taxa in relation to seawater carbonate chemistry (Figure B5). Each of these approaches has its distinct strengths and weaknesses. Bottle and microcosm experiments allow for high replication of multiple CO_2/pH treatments under well-controlled experimental conditions, thereby yielding high statistical power. However, they typically lack genetic and species diversity, competitive interaction, and the trophic complexity of natural systems, which complicates extrapolation of results to the real world. Field observations, on the other hand, cover the full range of biological interactions and environmental complexities, but they generally provide only a snapshot in time, with little or no information on the history of the observed biota and environmental conditions prior to sampling. The interpretation of field data in terms of dose/response relationships is often obscured by multiple environmental factors simultaneously varying in time and space and by the lack of replication.

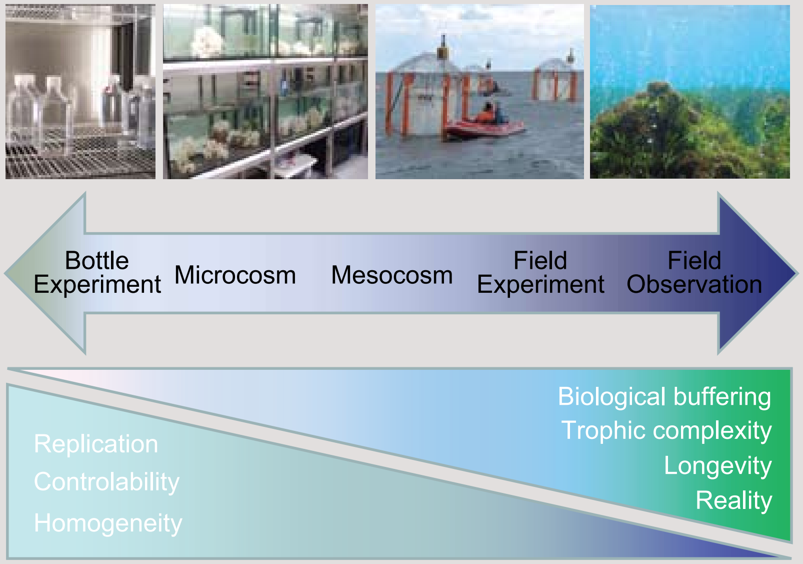

Figure B5: Experimental approaches with indication of their respective strengths and weaknesses. Photographs at top show phytoplankton bottle experiments in a culture chamber (left, courtesy of Kai Schulz, IFM-GEOMAR), cold-water corals in experimental aquaria (center left, courtesy of Armin Form, IFM-GEOMAR), an offshore mesocosm experiment in the Baltic Sea in spring 2009 (center right, Ulf Riebesell, IFM-GEOMAR), and a natural CO_2 venting site off Naples in the Mediterranean Sea (right; Riebesell, 2008). *Reprinted with permission from Macmillan Publishers Ltd., © 2008*

Mesocosms, experimental enclosures that are designed to approximate natural conditions and that allow manipulation of environmental factors, provide a powerful tool to link small-scale single species laboratory experiments with observational and correlative approaches applied in field surveys. A mesocosm study has an advantage over standard laboratory tests in that it maintains a natural community under close to natural, self-sustaining conditions, taking into account relevant aspects of natural systems such as indirect effects, biological compensation and recovery, and ecosystem resilience. Replicate enclosed populations can be experimentally manipulated and the same populations can be sampled repeatedly over time. Further advantages of flexible-wall, in situ enclosures are that a large volume of water and most of its associated organisms can be captured with minimal disturbance. The mesocosm approach is therefore often considered the experimental ecosystem closest to the real world, without losing the advantage of reliable reference conditions and replication. To improve understanding of the underlying mechanisms of observed responses, which are often difficult to infer from mesocosm results, and to facilitate scaling up mesocosm results, large-scale enclosure experiments should be closely integrated with well-controlled laboratory experiments and modeling of ecosystem responses.

Taking advantage of a recently developed mobile, flexible wall mesocosm system, EPOCA will conduct a joint mesocosm CO_2 perturbation experiment in the high Arctic, involving marine and atmospheric chemists, molecular and cell biologists, marine ecologists, and biogeochemists. A total of nine mesocosm units 2-m in diameter and 15-m deep, each containing approximately 45,000 liters of water, will be deployed in Kongsfjord off Ny-Ålesund on Svalbard. Carbonate chemistry of the enclosed water will initially be manipulated to cover a range of pCO_2 levels from preindustrial to projected year 2100 values (and possibly beyond) and will be allowed to float freely during the course of the experiment to mimic variations naturally occurring due to biological activity. The high level of scientific integration and cross-disciplinary collaboration of this study is expected to generate a comprehensive data set that lends itself to analyses of community-level ocean acidification sensitivities and ecosystem/biogeochemical model parameterizations.

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BOX 5. MODELING OCEAN ACIDIFICATION IN THE ARCTIC OCEAN

By Marco Steinacher, Fortunat Joos, and Thomas L. Frölicher

Ocean acidification in the Arctic is an important research focus in EPOCA. Oceanographic measurements demonstrate that Arctic surface water is already close to undersaturation with respect to aragonite (Jutterström and Anderson, 2005), and that undersaturation is imminent as fossil fuel carbon emissions continue to rise. Climate change is projected to amplify ocean acidification in the Arctic. Ocean acidification from business-as-usual, twenty-first century emissions is irreversible on human time scales.

Model results from nine modeling groups will become available within EPOCA to assess biogeochemical and ecosystem consequences of ocean acidification in the Arctic and in other regions of the world in a comprehensive analysis. EPOCA researchers will employ the full hierarchy of models from cost-efficient Earth System Models of Intermediate Complexity (EMICs), through high-resolution regional models, to state-of-the-art global coupled climate-biogeochemical models.

As an example, we briefly discuss results obtained with the NCAR Climate System Model forced with rising carbon emissions for the two Intergovernmental Panel on Climate Change business-as-usual emission scenarios (A2 and B1) until 2100 (Steinacher et al., 2009). The NCAR Climate System Model is a global climate model with fully coupled atmosphere, ocean, land, and sea-ice components, and it includes an interactive global carbon cycle. Here, the carbonate ion concentration $[CO_3^{--}]$ and the related saturation state for aragonite are used as indicators.

Undersaturation in the Arctic Ocean is imminent—expected to begin within the next decade for both scenarios (Figure B6). By the time atmospheric CO_2 exceeds 490 ppm (2040 in A2, 2050 in B1), more than half of the Arctic is projected to be undersaturated at the surface (annual mean). By the end of the twenty-first century and for the A2 case, undersaturation in the Arctic Ocean also occurs with respect to calcite.

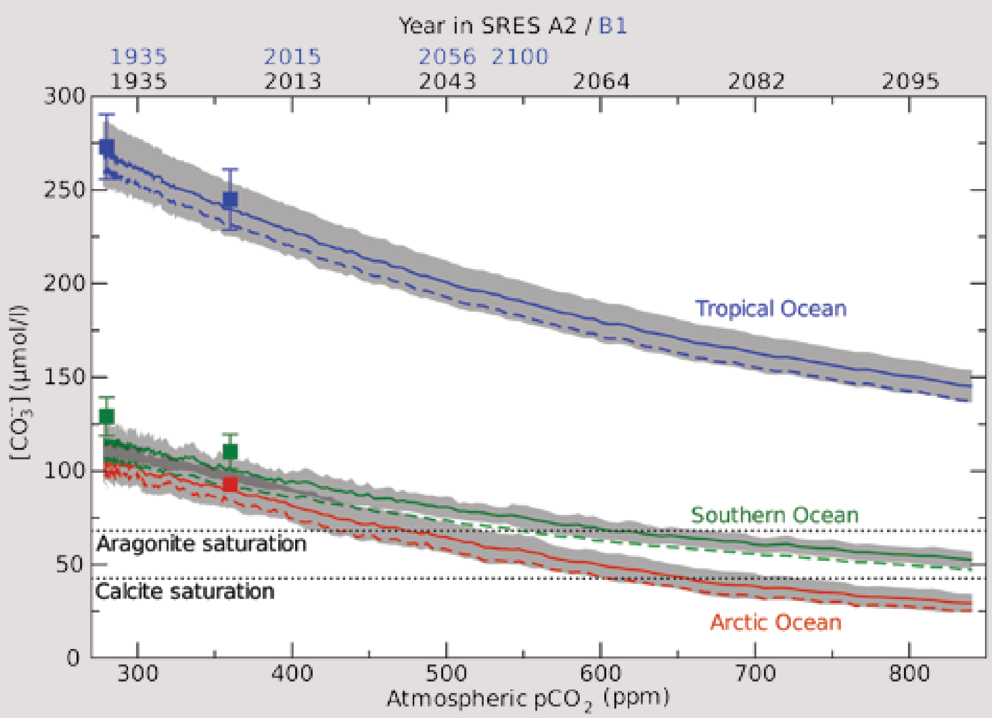

Figure B6. Projected surface water carbonate ion concentration versus projected atmospheric CO_2 (lower x-axis) and time (upper x-axis) for low (SRES B1) and high (SRES A2), business-as-usual emission scenarios. The figure shows modeled annual mean (solid line) and lowest monthly (dashed) concentrations averaged over the Arctic Ocean (red), the Southern Ocean (green), and the tropical ocean (blue), and spatial variability of annual mean concentrations within each region (shading, ± one standard deviation). Squares indicate observation-based estimates for the Southern Ocean and tropics (Global Ocean Data Analysis Project and World Ocean Atlas 2001 [http://www.nodc.noaa.gov/OC5/WOA01/pr_woa01.html], annual mean), and for summer conditions in the Arctic Ocean (CARINA [CARbon dioxide IN the Atlantic Ocean] database; http://cdiac.ornl.gov/oceans/datmet.html), with "error bars" indicating the spatial variability. Model results are from the NCAR CSM1.4-carbon model.

The main reasons for the vulnerability of the Arctic Ocean are (1) its naturally low saturation state, as documented by several oceanographic cruises, and (2) Arctic climate change amplifies acidification, in contrast to other regions like the Southern Ocean, where climate change has almost no effect in our simulations. Amplified climate change in the Arctic leads to a reduction in sea ice cover and surface freshening through ice melting, altered precipitation and evaporation, and river input. The dilution of surface waters alters the CO_2 partial pressure, which in combination with an increase in ice-free area, enhances the uptake of anthropogenic CO_2 through gas exchange by about 40%. Further, freshwater input decreases $[CO_3^{2-}]$ by dilution, whereas increased export of excess carbon out of the upper ocean and enhanced marine productivity counteract the reduction in $[CO_3^{2-}]$. Our study does not account for changes in riverine carbon fluxes. Considering all effects, the decrease in surface [CO_3^{2-}] in the Arctic Ocean is 34% higher than it would be without climate change in our model.

In contrast to other regions where the [CO_3^{2-}] decrease is basically a function of increasing atmospheric CO_2, the simulation of ocean acidification in the Arctic additionally relies on the model's ability to project climate change realistically. Major uncertainties are the magnitude and timing of sea ice cover reduction and changes in the freshwater balance. The simulated present-day ice cover in the NCAR model is larger than observed, and the projected reduction is moderate compared to other models. Considering the relatively low climate sensitivity of the model and recent projections of rapid summer sea ice decline, it is likely that the projected decrease in Arctic saturation represents a lower limit for a given scenario. Results from the EPOCA model suite will provide a more robust quantification of these effects.

Simulations in which emissions of carbon and other forcing agents are hypothetically stopped in years 2100 or 2000 allow us to investigate the legacy effects of historical and twenty-first century emissions. Undersaturation with respect to aragonite and calcite remains widespread in the Arctic for centuries even after cutting emissions in 2100 (recent work of authors Frölicher and Joos).

For the near future, it will be crucial that experimental scientists (see, e.g., Box 4) and modelers work hand in hand to improve understanding of how human carbon emissions affect the biogeochemical state of the ocean and how these changes affect the functioning and services provided by marine ecosystems. EPOCA's results will be needed to provide further guidance on emission reduction targets. Considering the precautionary principle mentioned in the United Nations Framework Convention on Climate Change, our subjective assessment is that atmospheric CO_2 should not exceed 450 ppm in order to avoid the risk of large-scale disruption to marine ecosystems.

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dissolution and driving seawater toward undersaturation of calcium carbonate. Put simply, undersaturation will not only render calcification more difficult but may also lead to corrosion of existing shells and skeletons.

Fifteen EPOCA scientists recently returned from the first large-scale field experiment of the project—a five-week-long campaign in Svalbard aimed at investigating the impact of ocean acidification on Arctic benthic organisms such as echinoderms, mollusks, crustaceans, and calcareous algae. The organisms were exposed to different levels of pCO_2 using indoor mesocosm setups. In 2010, about 40 EPOCA scientists will return to Svalbard to study pelagic communities using offshore mesocosm facilities (see Box 4).

Guide to Best Practices for Ocean Acidification Research and Data Reporting

Standardized data protocols and reporting are crucial for meaningful comparisons and collaboration within the ocean acidification field. Working with IOC-UNESCO, and with funding support from the Scientific Council on Oceanic Research (SCOR), the US Ocean Carbon Biogeochemistry program, and the Kiel Excellence Cluster *The Future Ocean*, EPOCA organized an international workshop on Best Practices for Ocean Acidification Research in Kiel, Germany, November 19–21, 2008. The meeting brought together approximately 40 scientists with expertise in different areas of ocean acidification research; the agenda covered seawater carbonate chemistry, experimental design of perturbation experiments, and measurements of CO_2-sensitive processes, as well

BOX 6. EPOCA OUTREACH ACTIVITIES

By Carol Turley, Kelvin Boot, Kelly-Marie Davidson, Dan Laffoley, and Philippe Saugier

EPOCA uses a variety of techniques to ensure that concern about ocean acidification is getting through to key audiences. The students of Ridgeway School in Plymouth, UK, formulated an innovative approach to engaging young people. Working with EPOCA scientists, they produced a hard-hitting, animated film, *The Other CO_2 Problem*, starring characters from King Poseidon's Kingdom beneath the sea (Figure B7). The entertaining film laments the fact that Doctorpus, Michelle Mussel, Derek the Diatom, and their friends are suffering as the ocean becomes more acidic; the film ends with Poseidon demanding that we terrestrials sort out the problem and stop pumping more CO_2 into the atmosphere to be absorbed by the sea.

The film has been previewed at two prestigious scientific meetings, first in Copenhagen in March 2009 where it was seen by more than 100 international scientists and policymakers attending the International Congress on Climate Change. Its second showing was at a meeting of the Royal Institution of Great Britain as part of a presentation by Carol Turley on ocean acidification. The film continues to attract media and press interest, including being featured in national TV news programs in the UK, particularly. The animation is available on the EPOCA Web site: http://www.epoca-project.eu/index.php/The-other-CO2-problem-animation.html. Among the ocean acidification science community, it has received many plaudits; for example, in an email to the author of this box following a viewing of the film, Ove Hoegh-Guldberg, University of Queensland, co-author of the Royal Society report on ocean acidification, said, "Brilliant. … This is one of the clearest communiques about the problems that the ocean faces from acidification. If only all of us scientists could be this clever at getting the message across! Well done students of Ridgeway School!"

The film highlights the concern surrounding ocean acidification and now forms part of a suite of supporting materials, including an EPOCA brochure.

Once teachers and their pupils have become aware of ocean acidification through movies, Web sites, and written materials, EPOCA can help them gain a greater understanding of the problem through engagement with CarboSchools. CarboSchools encourages longer-term educational projects through teacher-scientist partnerships supported locally by nine European institutes, in addition to teachers and scientists working individually. In these partnerships with real scientists, young Europeans conduct experiments on the impact of excessive greenhouse gases on climate, learn about climate research, and consider how CO_2 emissions might be reduced. Scientists and teachers cooperate over several months to give young people practical research experience through real investigations. Toward the end of each project, the pupils are encouraged to inform the wider community about climate change by, for example, producing articles, contributing to exhibitions, and attending conferences. Examples of projects, a library of experiments, and methodological advice are available at www.carboschools.org.

Figure B7. Pupils from Ridgeway School, Plymouth, working on the ocean acidification animation.

The young generation is important, but so are those whose concern is the immediate management of the ocean and the wider environment. The Reference User Group (RUG) concept has proved to be a highly successful mechanism for ensuring the relevance, user-friendliness, and outreach of research. EPOCA RUG members are from agencies, government departments, business, industry, and nongovernmental organizations, and they work with project scientists in a two-way process. First, they advise on the types of data, analyses, and products that will be most useful to managers, policy advisors, decision makers, and politicians. Second, EPOCA RUG members advise on the format and nature of key messages arising from the research project. They also advise on dissemination procedures for the project to ensure that the results from the project are provided to all potential end users of the information and that feedback on key science developments reaches their own sector or parent organization during the lifetime of the project.

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as data reporting and usage.

The participants are in the process of producing a “Guide to Best Practices for Ocean Acidification Research and Data Reporting” to ensure proper collaboration and comparisons of results within the ocean acidification research community. The guide has been subject to a peer review as well as an open review prior to publication, which is expected in early 2010. For more information on the guide, see page XX of this issue.

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