European Project on Ocean Acidification

Reporting

Project Information

<table>
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Final Report Summary - EPOCA (European Project on Ocean Acidification)

Project context and objectives:

Seawater carbonate chemistry is currently undergoing modifications at a rate of change that has not been observed throughout the history of Earth. Man-made carbon dioxide (CO2) invades the world's oceans at a rate of approximately 24 million tons per day, provoking chemical perturbations ultimately resulting in a reduction in pH and carbonate ion concentration. Whereas the chemical consequences of ocean acidification are perfectly foreseeable, the response of organisms and ecosystems to the phenomenon is still highly speculative, due to the scarce and sometimes conflicting data available. Throughout the very young history of ocean acidification research, the attention has often been devoted to the behaviour of calcifying organisms in a high CO2 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 CO2.

Ocean acidification has for many years stood in the shadow of its 'big brother' climate change, both originating from the same cause: the release of CO2 into the atmosphere by human activities. The effects of ocean acidification might be as dramatic as those of global warming, so providing another reason to drastically cut CO2 emissions. Emerging projects in Europe and in the United States (US) 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.

The European project on ocean acidification (EPOCA) was the first international research effort on ocean acidification. Launched in May 2008 with the overall goal to further our understanding of the biological, ecological, biogeochemical, and societal implications of ocean acidification, it comprised over 160 scientists from 32 institutions in 10 European countries. EPOCA was partly funded by the European Commission (EC, EUR 6.5 million for a total budget of EUR 16 million) and was launched in May 2008 for four years.

Overall objectives:
The overall goal of the EPOCA was to fill numerous gaps in the understanding of the consequences of ocean acidification.

EPOCA aimed to document the changes in ocean chemistry and geographical distribution of marine organisms across space and time. Paleo-reconstruction methods were 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.

EPOCA devoted much efforts 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 were investigated using a large array of techniques, ranging from molecular tools to physiological and ecological approaches. Perturbation experiments were carried out both in the laboratory and in the field. Key organisms were selected on the basis of their ecological, biogeochemical or socio-economic importance.

The modelling component of EPOCA integrated the chemical, biological and biogeochemical impacts of ocean acidification into biogeochemical, sediment and coupled ocean-climate models. Special attention was paid to feedbacks of physiological changes on the carbon, nitrogen, sulfur and iron cycles and in turn how these changes will affect and be affected by future climate change.

EPOCA assessed uncertainties, risks and thresholds (‘tipping points’) related to ocean acidification at molecular, cellular, organismal, local and global scales. It also assessed pathways of CO2 emissions required to avoid the identified thresholds and described the state change if these emissions are exceeded and the subsequent risk to the marine environment and Earth system.

EPOCA directly addressed all research items of the call item ENV.2007.1.1.3.1. It:

- improved the understanding of the past and present spatio-temporal changes of ocean acidification due to increasing CO2 uptake;
- determined the impacts of ocean acidification on marine biota, their physiology, ecosystems, the potential for acclimation and adaptation, impacts on elemental cycling and production of climate-relevant gases;
- improved understanding of future changes in ocean chemistry and biogeochemical feedbacks in terms of hotspots, uncertainties, and thresholds. It also improved the description of the carbon cycle in coupled ocean-climate models. The key element cycles investigated were carbon, nitrogen, sulfur and iron;
- synthesized information on tipping points.

EPOCA research themes

The research carried out through EPOCA was structured in 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 focused on such variations across space and time. Past variability in ocean chemistry was studied via paleo-reconstruction methods on archives such as cold-water corals and foraminifera. Continuous sampling and measurements in time-series stations and along transects, mostly in northern latitudes such as the Arctic Ocean and the North Atlantic, constituted 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 was devoted to the impacts of ocean acidification on marine biota, from planktonic species to higher trophic levels. Laboratory and mesocosm CO2 perturbation experiments combined with experimental approaches ranging from molecular to ecosystem scale were 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 how will these changes feed back on climate? Results from themes 1 and 2 were 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 was paid to the potential feedbacks of the biological changes in the carbon, nitrogen, sulphur and iron cycles.

Theme 4 - Synthesis, dissemination and outreach

What conclusions can be drawn when combining the results from themes 1, 2 and 3? Uncertainties, risks and potential critical thresholds or 'tipping points' associated with ocean acidification were communicated to policymakers and the general public in a comprehensible format and language. The EPOCA strategy aimed to contribute high quality science directly to expert groups and committees through the formation of the EPOCA reference user group (RUG) of stakeholders. The RUG advised EPOCA on the format and the nature of key messages arising from the project and on the dissemination procedures. The group put together several guides to policy makers in close cooperation with EPOCA scientists to ensure the scientific accuracy of the final products.

Interactions between the different themes were both ways. For example, theme 3 exploited information from themes 1 and 2 to predict future changes in ocean biogeochemistry and ecosystems. Similarly, results from theme 3 fed back into themes 1 and 2 by providing critical information on the expected temporal and spatial changes of ocean acidification and thus enable meaningful experimental designs.

Project results:

The text below is organised in two main parts. The first part contains shorter summaries of the main results within each theme and overarching activities, written in a language suitable for a larger public. The second
part list all the highlights put forward in the previous periodic reports.

EPOCA publications

EPOCA has generated a large number of critical data. 200 papers were published or are currently in press. They led to 175 presentations at meetings (122 oral presentations and 53 posters). Every fifth publication on ocean acidification during the period 2009-2011 was an EPOCA contribution. A summary of the major scientific results is presented below.

The EPOCA legacy - summary of major project results

Theme 1 - Changes in ocean chemistry and biogeography
(Theme leader: Jelle Bijma, AWI)

Within theme 1, paleo-reconstruction methods were used to investigate the response of organisms, mainly calcifying ones, to past changes in ocean acidification and to determine past variability in ocean carbonate chemistry (including nutrients and trace metals). Observations of carbonate chemistry as well as abundance and distribution of calcifiers in the present day ocean were also performed.

A major highlight within EPOCA was the discovery that ocean acidification in the Arctic near Iceland is proceeding faster and is more severe than expected. This was impressively shown at the 25 year time-series station (1984-2008) off the coast of Iceland. The surface water pH drop is 50 % faster than average annual rates at subtropical time-series stations in the North Atlantic and Pacific Oceans. The aragonite saturation horizon is shoaling at a rate of 4 m yr-1, encroaching on 800 km2 new ocean floor every year (Olafsson, 2009).

A synergistic effect of global warming on ocean acidification was highlighted by the finding of extreme under-saturation in the coastal Arctic ocean due to organic carbon input from thawing permafrost. This under-saturated water flows off the shelf into the deep central Arctic Ocean (Anderson et al., 2011).

For the western Arabian Sea, de Moel et al. (2009) found that light, thin-walled shells of the surface-water dwelling planktic foraminifer Globigerinoides ruber from the surface sediment are younger (based on 14C and 13C measurements) than the heavier, thicker-walled shells and concluded that this was indicative of ocean acidification on top of seasonal upwelling.

Another, rather puzzling, highlight is the response of the coccolithophorid Emiliania huxleyi to ocean acidification. Significantly higher percentages of over-calcified morphotypes were measured in the Bay of Biscay during winter, when conditions for calcification should be less favourable (Smith et al., 2012). In contrast, Beaufort et al. (2011) reported a significant overall decrease in coccolith mass and a decrease in coccoliths flux since the 1940s in sediment cores collected in the Western Pacific.

Theme 2: Biological and ecosystem responses, acclimation and adaptation
(Theme leader: Ulf Riebesell, GEOMAR)
Concerning the impacts of ocean acidification on marine life, EPOCA researchers studied a broad range of taxonomic groups, communities, habitats, and processes, with a regional focus on the European shelf seas and the high Arctic Ocean. This was achieved through a multidisciplinary approach combining laboratory studies, field experiments and observations with a suite of model studies simulating processes from the cellular and organism to the ecosystem level and from the 1D biogeochemical to the Earth system level. Major field activities were conducted during research cruises on the NW European continental shelf up to the Arctic, two joint mesocosm experiments in Svalbard on benthic organisms and processes in 2009 and on the pelagic system in 2010, and at natural CO2 venting site in the Mediterranean Sea.

There is now robust evidence that many calcifying organisms are adversely affected by ocean acidification. There is considerable variability in sensitivity between closely related species or even between different strains of the same species, with some species being tolerant to ocean acidification in the range of pCO2 levels projected until the end of this century. The observed variability thereby reflected the genetic diversity within populations (Langer et al., 2011; Hagino et al., 2011) or was related to regional differences between populations (Thomsen et al., 2010). In several groups early life stages proved particularly sensitive to ocean acidification (e.g. Gazeau et al., 2010). Delayed larval development under high CO2 was observed in crustaceans, bivalves and echinoderms.

Several studies highlighted the importance of long-term exposure to allow for proper acclimation. In some cases species which proved sensitive to ocean acidification in short-term incubations turned insensitive when kept under high pCO2 for extended periods of time (Form and Riebesell 2011, Dupont et al., in press). Negative impacts on the fitness of sea urchins were also observed when consecutive life-stages were exposed to high CO2.

Considerable progress was also made concerning the mechanisms underlying the observed responses for some taxonomic groups. For coccolithophores some of the transporters involved in calcium and carbon acquisition were identified (Mackinder et al., 2011; Richier et al., 2011) and the carbonate system parameters (i.e. pH and CO2 concentration) responsible for the observed response in photosynthetic and calcification determined. Very efficient mechanisms to regulate internal pH using proton pumps were identified in echinoderm larvae. A decapod crab was capable to compensate for ocean acidification by acid-base regulation, however, at the expense of metabolic repression.

As ocean acidification does not proceed in isolation, but co-occurs with changes in other environmental stressors, such as ocean warming, deoxygenation, and eutrophication, EPOCA research examined possible synergistic effects of multiple stressors (Pörtner, 2010). Several studies indicated that ocean acidification narrows the thermal tolerance of many organisms (e.g. Walther et al., 2009). Interacting effects of warming and acidification are expected to alter community structure and biodiversity (Hale et al., 2011).

Studies on natural communities along CO2 gradients (Charalampopoulou et al., 2011) and at CO2 venting sites proved to be a powerful test bed for results obtained in laboratory-based studies. Relating coccolith mass to seawater carbonate chemistry in different oceanographic regions as well as in sediment cores suggested much stronger sensitivities in coccolithophores than obtained in the laboratory (Beaufort et al., 2011). Drastic changes in benthic community composition and biodiversity were observed at volcanic
Several key processes driving biogeochemical cycling in the ocean are found to be sensitive to ocean acidification. This includes phytoplankton photosynthesis, nitrogen fixation by diazotrophic cyanobacteria and calcium carbonate production by calcifying plankton organisms. These responses cause changes in some key variables in ocean biogeochemistry, such as Redfield stoichiometry, the ratio of CaCO3 to organic matter in the export flux (termed rain ratio) and associated to this the ballasting of organic matter flux to the deep ocean (Gehlen et al., 2011). Changes in each of the processes impact the sequestration of carbon in the deep ocean, which feeds back to the climate system.

While EPOCA research has greatly progressed our understanding of biological sensitivities to ocean acidification, major unknowns still remain. Little is presently known about the impacts of biotic responses on competitive and trophic interactions. Will marine food webs still be the same in warmer and acidified oceans? Will organisms be able to adapt to ocean acidification? What will be the socioeconomic consequences of ocean change? These and other questions will be crucial when attempting to predict future developments of our oceans and the services they provide to humankind.

Theme 3: Biogeochemical impacts and feedbacks (Theme leader: James Orr, CEA/LSCE)

In theme 3, EPOCA modellers used coupled Earth system models (ESMs), forced global and regional ocean models, and a sediment model to project how ocean acidification will alter ocean biogeochemistry. Results from seven IPCC AR4-era ESMs were stored in a central, publicly available archive at ocmip5.ipsl.fr/FileFinderAR5. The same interface was extended to allow comparison with the ESMs from the Coupled Model Intercomparison Project, part of the ongoing assessment of the Intergovernmental Panel on Climate Change (IPCC AR5). Some of the key results of this theme are highlighted below:

- Results indicate that around 10% of Arctic surface waters will become undersaturated within 10 years during summer (Steinacher et al., 2009).
- Climate change has little effect on acidification except in the Arctic where it is exacerbated, mainly from freshening due to ice melt. Model formulations of CaCO3 production and dissolution as well as the particulate organic-to-inorganic carbon ratio were made to depend on CO2 levels, but there was little sensitivity in resulting air-sea CO2 fluxes. Similarly, explicitly modelling aragonite makes little difference (Gangstø et al. 2009).
- New forced ocean model simulations with variable C:N:P stoichiometry suggest that acidification-induced changes in primary productivity and carbon export (Tagliabue et al., 2011) will counter general reductions from climate change (Steinacher et al., 2010).
- New sensitivity tests indicate that coarse-resolution global models may generally underestimate the magnitude of variability of surface pH, saturation states, and air-sea CO2 flux by a factor of two or more.
- New regional model simulations have demonstrated the high vulnerability of some nearshore regions. In the Northwestern European Shelf Seas, simulations indicate large spatiotemporal variability, sometimes locally dominated by effects from river input and organic matter degradation, exacerbating acidification (Artioli et al., 2012). In the California Current System, an eastern boundary upwelling system (EBUS), there is a strong seasonal upwelling of undersaturated waters and a trend that will cause half the waters
above 250 m to become undersaturated by year 2050 (Hauri et al., 2009; Gruber et al., in press). Two other EBUS systems (Humboldt and Canary) also reveal heightened vulnerability.

- Projections from a global coastal sediment model indicate that alkalinity generation from benthic carbonate dissolution provides a negligible feedback against ocean acidification in coming centuries.

Some of the advances from the modelling initiative in EPOCA are detailed in three chapters of the book Ocean Acidification, which review recent and future changes in ocean carbonate chemistry, biogeochemical impacts, and effects from climate-change mitigation (Orr, 2011; Gehlen et al., 2011; Joos et al., 2011).

Theme 4: Synthesis, dissemination and outreach (Theme leader: Carol Turley, PML)

A highlight of EPOCA is its significant impact in raising awareness on ocean acidification worldwide through contributions to major policy activities, scientific assessments (e.g. IPCC AR5) as well as reports for policy makers and other research-users available on the EPOCA website (see http://www.epoca-project.eu/index.php/dissemination-a-media-center.html online). The EPOCA blog (see http://oceanacidification.wordpress.com/ online) has been the first point of call for researchers and policy makers for new science, policy and media information on ocean acidification.

The EPOCA ocean acidification reference user group (OA-RUG), formed in 2008, rapidly evolved, firstly incorporating United Kingdom, German and Mediterranean research programmes and very recently other countries to form the international Ocean Acidification Reference User Group (iOA-RUG). The three multilingual guides outline the essential facts for policy makers and decision-makers on ocean acidification and have been scrutinised by the scientific members of the RUG (themselves members of the research projects) to ensure scientific integrity.

EPOCA joined with a range of partners on outreach. Examples are, ocean acidification: frequently asked questions in response to the growing research across disciplines and the increasing need for clear answers by experts, a range of other policy documents including the recently produced 'Hot, sour and breathless: Ocean under stress (see http://www.oceanunderstress.com online) and side- and media-events and exhibition stands at the United Nations Framework Convention on Climate Change Congress of Parties (UNFCCC COPs), the Planet Under Pressure Symposium, and the Rio+20 Earth Summit.

EPOCA worked with 11-15 year old students from Ridgeway School in Plymouth, who made their concerns about the state of the world’s oceans clear through a hard hitting, award winning animation ‘The other CO2 problem’, suitable for children and policy makers alike (see http://www.youtube.com/watch?v=55D8TGRsl4k online) and now available in several languages. The movie 'Tipping point' mostly describes EPOCA research and has received three awards including the ‘Best scientific movie’ at the Mediterranean film festival. Both have been shown at science and policy meetings around the world and copies distributed worldwide.

An editorial, ‘The societal challenge of ocean acidification’, addressed for the first time the issue of vulnerable regions and biodiversity and how this would be a challenge for policy makers. The ‘Guide to
best practices for ocean acidification research and data reporting (see [http://www.epoca-project.eu/index.php/guide-to-best-practices-for-ocean-acidification-research-and-data-reporting.html](http://www.epoca-project.eu/index.php/guide-to-best-practices-for-ocean-acidification-research-and-data-reporting.html) online) regroups standards and guidelines on ocean acidification research and has been widely distributed to the international scientific community. 'Ocean acidification' edited by Gattuso and Hansson, the EPOCA coordinator and manager, is the first book on ocean acidification with the majority of the synthesis chapters written by EPOCA experts.

Overarching science activities: data management, best practices guidelines and book reviewing the state-of-the-art.

Management of EPOCA data and compilation of ocean acidification data

EPOCA has maintained two databases; one on observational and experimental data, the other one on modelling data.

Observational and experimental data

This part of the data management activities consisted of two efforts:

(i) the management of data created by EPOCA and
(ii) the archiving of all data on the biological response to ocean acidification published in the literature.

The latter is known as the EPOCA/EUR-OCEANS data compilation on the effects of ocean acidification and is described in Nisumaa et al., 2010. The EPOCA database now contains 137 datasets (99 laboratory or field experiments, 18 paleo experiments, 11 cruises and 9 other field observations) and the EPOCA/EUR-OCEANS data rescue collection holds 273 datasets. All datasets will remain accessible from Pangaea/WDC Mare after the end of EPOCA. It is hoped that the data compilation maintained by EPOCA for the past four years will be continued through an international coordinated effort.

EPOCA model-output archive

The project's model-output archive was enhanced in number of models and ease of access during the last year of the project and now contains output from seven Earth system models (ESM) from the IPCC AR4 era on a common server, through a publicly-available and user friendly interface [ocmip5.ipsl.fr/FileFinderAR5](http://ocmip5.ipsl.fr/FileFinderAR5). Through the same interface, a new parallel archive containing results from the latest generation of ESMs that have contributed to the 'Coupled model intercomparison project' (CMIP5), the foundation for the ongoing IPCC AR5 assessment has been added. The new CMIP5 archive currently includes output from 13 AR5-era ESMs. For compatibility, the format of the AR4 model output has been converted to the format used in CMIP5.

Guide to best practices in ocean acidification research and data reporting

One of the most important tasks of EPOCA was to synthesise technical guidelines on how to perform ocean acidification experiments. Indeed, due to its cross-cutting nature, research on ocean acidification brings together a wide spectrum of disciplines, from palaeo- and chemical oceanography, marine
biogeochemistry and climate modelling, to marine ecology, physiology, and molecular and evolutionary biology. These various scientific communities have their own disciplinary heritage, and frequently use specific terminology and research approaches and methodologies. Moreover, researchers, post-doctoral investigators and PhD students with no or limited previous experience in ocean acidification research constantly enter the field. To ensure comparability of the large number of data generated and achieve the highest possible data quality, it is thus important to agree on standardised protocols. EPOCA took the lead in putting together the community reviewed ‘Guide to best practices in ocean acidification research and data reporting’, which has proved to be one of the most successful and valued products of the project. The first edition was launched in May 2010 and is available online and in print (see http://www.epoca-project.eu/index.php/guide-to-best-practices-for-ocean-acidification-research-and-data-reporting.html online). The guide includes chapters on seawater carbonate chemistry, experimental design of perturbation experiments, measurements of CO2-sensitive processes and data reporting and usage. Following a considerable interest from the community, a second edition was printed in August 2011. More than 1000 copies have been distributed in less than two years.

Ocean acidification - the first book on the subject

‘Ocean acidification’ was published by Oxford University Press in September 2011. This research level text is the first to synthesise the very latest understanding of the consequences of ocean acidification, with the intention of informing both future research agendas and marine management policy. 14 out of the 15 chapters are authored by EPOCA scientists and each chapter is a synthesis of a field of ocean acidification research. The chapters cover the history and background of the field, the carbonate chemistry, past ocean acidification events, impact on several groups of marine organisms and ecosystems, climate sensitive biogases, biogeochemical consequences, future ocean acidification associated with mitigation and non-mitigation scenarios and pathways of CO2 stabilisation as well as policy implications and an assessment of the the uncertainties, risks and thresholds. 'Ocean acidification' is suitable for graduate level students as well as professional researchers in oceanography and marine biology. It is also of relevance and use to a more general audience of marine scientists and managers interested in the effects and potential impacts of ocean acidification.

EPOCA articles cited


Beaufort L., Probert I., de Garidel-Thoron T., Bendif E. M., Ruiz-Pino D., Metzl N., Goyet C., Buchet N.,


Tagliabue A., Bopp L. and Gehlen M., 2011. The response of marine carbon and nutrient cycles to ocean


EPOCA highlights from the duration of the project (listed according to themes)

Theme 1 highlights over the four-year period:

- Both ocean acidification and seasonal upwelling are responsible for the presence of light foraminiferan shells in the top of the sediment.
- Age offsets among different biogenic and lithogenic components of sediment cores revealed by numerical modeling.
- In the Iceland Sea, pH declines at a rate 50 % faster than average yearly rates at two subtropical time series stations, BATS and ESTOC.
- Degradation of organic matter in the Laptev and western East Siberian Seas leads to elevated pCO2 and low degrees of aragonite saturation state, even in the surface water.
- Coccoliths seem to have become overcalcified in winter.
- The boron isotopic ratio, a proxy of pH, of North Atlantic deep-sea corals is relatively stable throughout the Holocene but the most modern samples exhibit a drop in 11B values of up 1.2 which may indicate deep-water acidification in this area.
- The decrease in summer sea ice in the Arctic Ocean could increase the uptake of atmospheric CO2 thus lowering pH. In the Siberian shelf, the degradation of organic matter has a major impact causing high pCO2 and low pH levels.
- Calcium carbonate concentration is not a good monitoring variable for ocean acidification because CaCO3 particles include material coming from land in addition to shells of living plankton.
- Documentation of extreme undersaturation of the coastal Arctic ocean due to organic carbon input from thawing permafrost. This under-saturated water flows off the shelf into the deep central Arctic Ocean (Anderson et al., 2011).
- Contradiction between the response of coccolithophores to ocean acidification, measured by the teams from NOCS and CEREGE. While NOCS measured significantly higher percentages of overcalcified Emiliania huxleyi morphotypes in the Bay of Biscay during winter, when conditions for calcification should be less optimal, Beaufort et al. (2011) report a significant overall decrease in coccolith mass since the 1940s globally.
- Model analysis on what could be interpreted as carbonate chemistry 'tipping points' has been published (Hönisch et al., 2012).

Theme 2 highlights over the four-year period:
The first quantitative results on CO2/pH sensitivity of thecosome pteropods obtained by Comeau et al. (2009), who investigated Limacina helicina, a key species of Arctic ecosystems. Calcification, which was estimated using a fluorochrome and the radioisotope 45Ca, exhibited a 28 % decrease at a pH value expected for 2100 compared to the present pH value.

The first results on CO2/pH sensitivity of the cold water coral Lophelia pertusa obtained by Maier et al. (2009). Lowering pH by 0.15 and 0.3 units relative to the ambient level resulted in calcification being reduced by 30 and 56 %. Lower pH reduced calcification more in fast growing, young polyps (59 % reduction) than in older polyps (40 % reduction). Interestingly, L. pertusa exhibited positive net calcification at an aragonite saturation state (a) below 1.

Evidence on the effect of elevated CO2 on the development and hatching success of embryos of the barnacle Semibalanus balanoides living in intertidal waters.

Evidence of a synergistic impact of CO2 and temperature on the cold-eurythermal spider crab Hyas araneus. Animals exposed to 380, 710, and 3000 ppm CO2 were exposed to progressive short term cooling from 10 to 0 °C and to warming from 10 to 25 °C. Heart rate increased during warming until a critical temperature (Tc) was reached. The putative Tc under normocapnia (380 ppm CO2) was presumably >25 °C, from where it fell to 23.5 °C under 710 ppm and then 21.1 °C under 3000 ppm. At the same time, thermal sensitivity, as seen in the Q10 values of heart rate, rose with increasing CO2 concentration in the warmth. These results suggest a narrowing of the thermal window of Hyas araneus under moderate increases in CO2 levels (Walther et al., 2009).

Evidence of adverse effects of elevated CO2 on the cyanobacterium Nodularia spumigena, a heterocystous bloom-forming diazotroph of the Baltic Sea, contrasting earlier findings on stimulating effects of elevated CO2 on the cyanobacterium Trichodesmium, a predominant diazotroph (nitrogen-fixing) in large parts of the oligotrophic oceans. Possible explanations for the contrasting physiological responses of Nodularia compared to Trichodesmium may be found in the different ecological strategies of non-heterocystous (Trichodesmium) and heterocystous (Nodularia) cyanobacteria.

First perturbation experiments carried out on benthic Arctic organisms.

CO2 fertilisation of Trichodesmium: In a review article, Kranz et al. (2011) summarises the current knowledge for this key nitrogen fixer, focusing on underlying processes like carbon acquisition and N2 fixation and CO2-dependent shifts in energy allocation. Possible ecological and biogeochemical implications resulting from the CO2 fertilisation on Trichodesmium are discussed, indicating that Trichodesmium will be a winner of ocean acidification with large implication for the future C and N cycling. This genus may furthermore play another and unforeseen role in biogeochemical cycling due to its ability to induce CaCO3 precipitation (Kranz et al. 2010).

Dissolution of pterodod shells: A strong relationship between the aragonite saturation state (a) and the calcium carbonate precipitation rate was found for both Arctic and Mediterranean pteropods. Dissolution of the shell in undersaturated conditions has also been reported on adult and juvenile Mediterranean
pteropods (Comeau et al., 2010a, b).

Impact of ocean acidification on calcification of zooxanthellate scleractinian corals from the Mediterranean: Studies used the Mediterranean zooxanthellate coral Cladocora caespitosa, to show that an increase in pCO2, in the range predicted for 2100, does not reduce its calcification rate. Therefore, the conventional belief that calcification rates will be affected by ocean acidification may not be widespread in temperate corals. Seasonal change in temperature is the predominant factor controlling photosynthesis, respiration, calcification and symbiont density. An increase in pCO2, alone or in combination with elevated temperature had no significant effect on photosynthesis, photosynthetic efficiency and calcification. The lack of sensitivity in C. caespitosa to elevated pCO2 might be due to its slow growth rates, which seem to be more dependent on temperature than on the saturation state of calcium carbonate in the range projected for the end of the century.

Svalbard mesocosm experiment 2010: To study the impacts of ocean acidification on plankton communities, a group of 35 researchers conducted the first major CO2 perturbation experiment in the Arctic Ocean. Led by the Leibniz Institute of Marine Sciences (IFM-GEOMAR) nine mesocosms were set out in the Kongsfjord off the north-west coast of Svalbard. Each of the 17 m long test tubes held about 50 cubic metres of seawater. The enclosed plankton community was exposed to a range of different CO2 and pH levels, representative for glacial and projected mid-next-century levels and was closely monitored over a five-week period. The EPOCA scientists, who stayed at the Ny Ålesund research station, sampled the mesocosms daily from zodiacs with plankton nets, water samplers and pumps, and conducted measurements with profiling sensors and in situ probes. EPOCA's 2010 mesocosm campaign, which involved molecular and cell biologists, marine ecologists and biogeochemists, ocean and atmospheric chemists, addressed a range of urgent questions concerning the impacts of ocean acidification on Arctic ecosystems. How will ocean acidification affect the production of food at the base of the Arctic food web and its transfer to consumers at higher levels? How will ocean acidification influence competition and trophic interactions at various levels of the pelagic ecosystem? Will there be winners and losers of ocean acidification? Another set of questions concerns the possible consequences for the cycling of key elements. Will ocean acidification affect the sequestration of carbon in the Arctic ocean? Will it change the turn-over and balance between the primary building blocks of life such as carbon, nitrogen and phosphorus? A third set of questions concerns the exchange of climate-relevant gases between ocean and atmosphere. Will ocean acidification affect the production of these gases and if so, will it amplify or dampen global climate change? The scientists collected nearly 15 000 samples and acquired data for over 45 parameters characterising the responses of the Arctic ecosystem to ocean acidification. The results of this study, which will be presented at various international conferences in 2011, are expected to provide the first comprehensive insight into the sensitivities of the Arctic ecosystem to a rapidly acidifying ocean.

Ocean acidification-associated variations in DMS and DMSP: During the Svalbard oelagic mesocosm experiments daily monitoring of the concentrations of DMS, it's precursor DMSP, and a range of volatile halogenated compounds were undertaken. pH-associated variations in DMS and DMSP concentrations were observed, particularly following the addition of nutrients to the mesocosms. Significantly reduced DMS concentrations occurred at decreased pH levels. Although possibly higher at reduced pH, variations in DMSP concentrations were much less obvious, indicating reduced efficiency in the transformation of
Impacts of ocean acidification and elevated temperature on an intact marine invertebrate community: A mesocosm experiment was conducted to quantify the effects of reduced pH and elevated temperature on an intact marine invertebrate community (Hale et al., 2011). After 60 days exposure communities showed significant changes in structure and lower diversity in response to reduced pH.

Impact of long term (up to 16 months) and trans-life-cycle (carry-over effects) acclimation to near-future ocean acidification on the green sea urchin Strongylocentrotus droebachiensis. This study highlights the importance of time of exposure and carry-over effects to assess the real impact of ocean acidification. For example, negative impacts on fitness were observed when subsequent life-stages were exposed to low pH with little or no effect when single life-stage were exposed to low pH (Dupont et al., in press).

Ocean acidification effects on mesopelagic prokaryotic communities: Eight short-term (one week) and two long-term (two months) experiments were performed during a seasonal cycle with mesopelagic prokaryotic communities. Changing the pCO2 concentration caused occasionally strong changes in prokaryotic, viral and and flagellate abundances and TEP concentration, however, no consistent trends during the seasonal cycle were detected. CO2 level had a significant effect on transcript level of ammonia oxidizing bacteria and the diversity of ammonia oxidizing archaea, but limited effect on nitrogen fluxes from sediments. Increasing pCO2 levels from 400 to 1000 µatm affected the community composition of bacteria and archaea and the respiration rate of mesopelagic prokaryotes in long-term experiments (2 months), however, trends differed between experiments.

Coral and mollusc resistance to ocean acidification adversely affected by warming: Reduced skeletal growth under increased CO2 levels has already been shown for corals, molluscs and many other marine organisms. The impact of acidification on the ability of individual species to calcify has remained elusive, however, as measuring net calcification fails to disentangle the relative contributions of gross calcification and dissolution rates on growth. Rodolfo-Metalpa et al. (2011) show that corals and molluscs transplanted along gradients of carbonate saturation state at Mediterranean CO2 vents are able to calcify and grow at even faster than normal rates when exposed to the high CO2 levels projected for the next 300 years. Calciifers remain at risk, however, owing to the dissolution of exposed shells and skeletons that occurs as pH levels fall. Their results show that tissues and external organic layers play a major role in protecting shells and skeletons from corrosive sea water, limiting dissolution and allowing organisms to calcify. Their combined field and laboratory results demonstrate that the adverse effects of global warming are exacerbated when high temperatures coincide with acidification.

Severe tissue damage in Atlantic cod larvae under increasing ocean acidification: In teleost fishes, early life-history stages are particularly vulnerable as they lack specialized internal pH regulatory mechanisms. So far, impacts of relevant CO2 concentrations on larval fish have been found in behaviour and otolith size, mainly in tropical, non-commercial species. Frommel et al. (2011) show detrimental effects of ocean acidification on the development of a mass-spawning fish species of high commercial importance. Atlantic cod larvae were reared at three levels of CO2, (1) present day, (2) end of next century and (3) an extreme, coastal upwelling scenario, in a long-term (2 months) mesocosm experiment. Exposure to CO2 resulted in severe to lethal tissue damage in many internal organs, with the degree of damage increasing with CO2
concentration. As larval survival is the bottleneck to recruitment, ocean acidification has the potential to act as an additional source of natural mortality, affecting populations of already exploited fish stocks.

Sensitivity of coccolithophores to carbonate chemistry and ocean acidification: Coccolithophores are abundant phytoplankton that are responsible for a large part of modern oceanic carbonate production. Beaufort et al. (2011) quantified the calcite mass of dominant coccolithophores in the present ocean and over the past forty thousand years, and found a marked pattern of decreasing calcification with increasing partial pressure of CO2 and concomitant decreasing concentrations of CO3^2−. Their analyses revealed that differentially calcified species and morphotypes are distributed in the ocean according to carbonate chemistry. A substantial impact on the marine carbon cycle might be expected upon extrapolation of this correlation to predicted ocean acidification in the future. However, their discovery of a heavily calcified Emiliania huxleyi morphotype in modern waters with low pH highlights the complexity of assemblage-level responses to environmental forcing factors.

Acclimation to ocean acidification during long-term CO2 exposure in the cold-water coral Lophelia pertusa: Our present understanding of the impacts of ocean acidification on marine life relies heavily on results from short-term CO2 perturbation studies. Form and Riebesell (2012) present results from the first long-term CO2 perturbation study on the dominant reef-building cold-water coral Lophelia pertusa and relate them to results from a short-term study to compare the effect of exposure time on the coral’s responses. Short-term (1 week) high CO2 exposure resulted in a decline of calcification by 26 - 29 % for a pH decrease of 0.1 units and net dissolution of calcium carbonate. In contrast, L. pertusa was capable to acclimate to acidified conditions in long-term (six months) incubations, leading to even slightly enhanced rates of calcification. Net growth is sustained even in waters sub-saturated with respect to aragonite. Acclimation to seawater acidification did not cause a measurable increase in metabolic rates. This is the first evidence of successful acclimation in a coral species to ocean acidification, emphasising the general need for long-term incubations in ocean acidification research. To conclude on the sensitivity of cold-water coral reefs to future ocean acidification further ecophysiological studies are necessary which should also encompass the role of food availability and rising temperatures.

Ocean acidification-induced food quality deterioration constrains trophic transfer: Our present understanding of ocean acidification impacts on marine organisms is almost entirely limited to single species responses. Consequences for food web interactions are, however, still unknown. Indirect effects can be expected for consumers by changing the nutritional quality of their prey. Rossol et al. (2012) used a laboratory experiment to test potential effects of ocean acidification on algal fatty acid (FA) composition and resulting copepod growth. They show that elevated CO2 significantly changed the FA concentration and composition of the diatom Thalassiosira pseudonana, which constrained growth and reproduction of the copepod Acartia tonsa. A significant decline in both total FAs (28.1 to 17.4 fg cell21) and the ratio of long-chain polyunsaturated to saturated fatty acids (PUFA:SFA) of food algae cultured under elevated (750 µatm) compared to present day (380 µatm) pCO2 was directly translated to copepods. The proportion of total essential FAs declined almost tenfold in copepods and the contribution of saturated fatty acids (SFAs) tripled at high CO2. This rapid and reversible CO2-dependent shift in FA concentration and composition caused a decrease in both copepod somatic growth and egg production from 34 to 5 eggs per female per day. Because the diatom-copepod link supports some of the most productive ecosystems in the world, this study demonstrates that ocean acidification can have far-reaching consequences for
ocean food webs by changing the nutritional quality of essential macromolecules in primary producers that cascade up the food web.

Svalbard mesocosm experiment 2010: A second data workshop on the 2010 Svalbard mesocosm experiment was held at GEOMAR in Kiel on 15 - 16 September 2011. The goals of the workshop were to:

- present and discuss the various data sets
- resolve discrepancies between individual data sets
- decide on manuscripts and authorship
- agree on publication strategy.

Presently 16 manuscripts are in preparation covering aspects from effects of ocean acidification on virolysis, bacterial and phytoplankton community dynamics and production, micro- and mesozooplankton dynamics, to community production, elemental cycling and carbon budgeting, production of climate relevant gases, and air-sea gas exchange. It was decided to publish a large fraction of the manuscript in a special issue of Biogeosciences (BG). A proposal for a special issue entitled 'Arctic ocean acidification: pelagic ecosystem and biogeochemical responses during a mesocosm study' (guest editors: U. Riebesell, J.-P. Gattuso, J. Middelburg, and F. Thingstad) was made to BG and accepted by the chief editors. Manuscripts can be submitted between 1 January and 31 July 2012.

Most of the Svalbard mesocosm data have been archived in the EPOCA database (with restricted access) and are available to all participants of the study.

Theme 3 highlights over the four-year period:

Models show that 10 % of surface waters will become undersaturated within 10 years during summer (Steinacher et al., 2009) during winter, such undersaturation probably already occurred by 1990. Joint analysis of associated changes in global-scale productivity is also underway (Steinacher et al., 2009). A cost efficient ESM is also being developed.

Regional models were used to assess the current state and future changes of pH, CaCO3 saturation states in regional domains important for the economy of Europe, including the Northwestern European Shelf Seas (Blackford et al., 2010) and the Canary current system. A similar configuration of the ROMS model used in the Canary current system is used in the California current system, which is another eastern boundary. In that region, there is substantial variability in surface water pH system and saturation states, largely driven by seasonal upwelling of corrosive waters and the interactions of transport and biological production (Hauri et al., 2009). The volume of waters in surface waters that have an a < 1.5 has increased from 0 % in pre-industrial times to more than 10 % at present. The annual-mean aragonite saturation horizon is projected to shoal into the euphotic zone in the near future. By 2050, the volume of water in the upper 250 m with an aragonite saturation state of > 2 is projected to disappear, while 50 % of the volume is projected to be undersaturated with regard to aragonite.

CO2-dependent formulations for CaCO3 production and dissolution and the organic-to-inorganic carbon rain ratio were developed and improved using new ocean-modelSimulations and sensitivity tests.
Preliminary results indicate that for a given scenario, projected geochemical variables including pH and saturation states are relatively insensitive to the model formulations, and even whether aragonite is accounted for in addition to calcite or not.

Model resolution has been improved to start to better account for the role eddies, and how they affect ocean acidification in the coastal environment (Hauri et al., 2009) and at the global scale. For the latter, the PISCES model has been successfully coupled to the 1/2 global version of the NEMO model, and results from the first test simulations are under scrutiny.

New simulations from the EPOCA earth system models were completed using the new representative concentration pathways (RCPs). These provide a strong contribution from EPOCA to the ongoing IPCC AR5 assessment.

New transient simulations up to 2050 demonstrate the accelerated rate of acidification in the California Current System (CCS), particularly in the north. By 2050, the aragonite saturation horizon shoals by 180 m to reach an annual average depth of 40 m.

A model of the Northwestern European Seas forced with an atmospheric CO2 of 1000 ppm projects that seawater will become corrosive to aragonite over the entire shelf during winter; in the stratified areas on the shelf, this undersaturation persists throughout the year.

Global and basin-scale models dramatically underestimate the magnitude, extent, and evolution of ocean acidification in Eastern boundary upwelling systems compared to high resolution regional models.

Climate change is projected to shift the total abundance and diversity of foraminifera deeper and polewards into waters that have lower and decreasing calcite saturation states.

A decrease in marine emissions of two major climate-active gases is projected for the end of the 21st century.

The changes in CaCO3 production and dissolution induced by ocean acidification provide only a small negative feedback on atmospheric CO2.

A Pinatubo-scale volcanic eruption has a much lower influence on ocean pH than past anthropogenic emissions.

The volume of supersaturated water providing habitat to calcifying organisms is reduced from preindustrial 40 to 25 % in 2100 and to 10 % in 2300 for a high 21st century emission commitment scenario.

The largest simulated pH changes worldwide occur in Arctic surface waters, where hydrogen ion concentration increases by up to 185 %. Projected climate change amplifies the decrease in Arctic surface mean saturation and pH by more than 20 %, mainly due to freshening and increased carbon uptake in response to sea ice retreat.

A chapter in the new book 'Ocean acidification' reviews recent and future changes in ocean carbonate
chemistry (Orr, 2011). A second chapter in the same book reviews ocean biogeochemical impacts of ocean acidification (Gehlen et al., 2011). A third chapter in the same book quantitatively assesses the effects of climate-change mitigation on projections of ocean acidification (Joos et al., 2011).

Output from simulations with seven ESMs forced under the IPCC SRES A2 scenario have been made publicly available in a central archive and are now accessible via an easy-to-use interface (ocmip5.ipsl.fr/FileFinderAR5). Joint analysis of these models has been led by four different EPOCA partners (UBERN, CEA/LSCE, UiB, GEOMAR; see D12.5 deliverable report).

New sensitivity tests suggest that coarse-resolution global models may generally underestimate the magnitude of variability of surface pH, saturation states, and air-sea CO2 flux by a factor of two or more (D10.4 deliverable report).

Other sensitivity tests indicate that different reanalysis products that are used to force ocean models (hindcast simulations over the last 50 years) lead to different trends in some regions (D10.4 deliverable report).

Analyses of multiple earth system models indicate that:

(i) future Arctic surface pH would decline by nearly 1 pH unit under the most severe RCP scenario (Orr et al., poster 2012 EPOCA meeting) and that
(ii) North Atlantic bottom-water pH will decline by > 0.2 units by the end of the century (Gehlen et al., in preparation).

Another multi-model ESM comparison has investigated the relationship between the North Atlantic Oscillation (NAO), a major climate index, and the variability of the North Atlantic's carbon cycle (Keller et al., in preparation).

Yet another multi-model study has compared simulated declines in subsurface dissolved O2 with increasing CO2 and warming (Cocco et al., in preparation).

New regional model simulations have demonstrated the high vulnerability of some nearshore regions, including those in the Arctic and Norwegian shelf (Bellerby et al., in preparation), eastern boundary upwelling systems (Hauri et al., in prep.), and bottom waters of the shallow North Sea (Artioli et al., 2012).

A regional model of the Northwestern European Shelf Seas (PML) demonstrated large spatial and temporal variability of acidification and the importance of exacerbating factors that cause waters to become undersaturated with respect to aragonite, e.g. river input (German bight) and degradation of organic matter (in bottom waters of the North Sea). But results are sensitive to conditions imposed at open boundaries and for river input (Artioli et al., poster at final EPOCA meeting, Artioli et al., in preparation).

One regional ocean modelling system (ROMS) was used in three different eastern boundary up-welling systems (EBUS) revealing their generally heightened vulnerability to acidification. Results indicate that the Humboldt current system is most vulnerable, the California current system is not as vulnerable but still unusually sensitive and variable, and the Canary current system is least vulnerable (Artmann-Korpuenski
A global ESM study implemented a relationship between pH and the climate-relevant gas DMS, finding that DMS production would decline by 26% in 2100 due to effects from both climate change and ocean acidification (Six et al., in preparation).

A cost-efficient Earth System Model of intermediate complexity model was used with 1000 Monte-Carlo (probabilistic) simulations to tune model parameters to be consistent with available large-scale data sets, thus narrowing uncertainties in projections (D11.6 report).

Theme 4 highlights over the four-year period:

- Continuous updating of EPOCA website, blog and Twitter makes them excellent and well recognised worldwide resources on ocean acidification for scientists and stakeholders alike.
- An archive of EPOCA’s results, achievements and deliverables.
- Meetings of iOA-RUG and the RUG publications aimed at policy makers launched at COP 15, a RUG meeting in Moanaco in 2010 and at COP17. Translations of the document in multiple languages are available.
- Tipping points session at the EPOCA annual meetings with presentations from members of the tipping point group and panel discussions and debates.
- Publication of the first book on ocean acidification with major contributions from EPOCA scientists (editors and authors) reviewing different areas of ocean acidification science, including risks and uncertainties.
- Publication of paper on societal challenge of ocean acidification in leading journal and further take up of accessible figures from it by the RUG, Nature and IPCC.
- Influential input from EPOCA scientists via roles on national and international committees, working groups etc.
- Production of EPOCA outreach products (e.g. RUG guides, FAQ and ocean stress guide for UNFCCC COP17 and Rio+20).
- EPOCA influence and input to major knowledge exchange activities (e.g. at UNFCCC SBSTA and COP15, 16 and 17, Planet under Pressure conference and the lead up to Rio+20) including exhibition stands, information documents for policy makers and presentations at side events in collaboration with other science organisations.
- French version of the EPOCA animation made by English school children on ocean acidification. Spanish, Italian and Catalan versions available through collaboration with MedSeA.
- EPOCA lead in publication of a questionnaire on ocean acidification to elicit expert opinion on vulnerabilities so that consensus statements can be made.
- Major input from EPOCA scientists in the IPCC 5th AR on climate change as lead authors, chapter leaders, review editors and reviewers.
- Major contribution to science understanding by substantial number of peer reviewed science publications.
- EPOCA presentations at key scientific and stake-holder conferences.

- Trusted advice to stakeholders on ocean acidification (e.g. input to the Convention on Biological
Diversity).

Related documents

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