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Impacts of Ocean Acidification

Contents

1 • Foreword
2 • Introduction and rationale
3 • Ocean acidification and its impacts
6 • Recommendations for European Actions

Foreword

There is growing scientific evidence that, as a result of increasing anthropogenic carbon dioxide (CO_2) emissions, absorption of CO_2 by the oceans has already noticeably increased the average oceanic acidity from pre-industrial levels. This global threat requires a global response. According to the Intergovernmental Panel on Climate Change (IPCC), continuing CO_2 emissions in line with current trends could make the oceans up to 150% more acidic by 2100 than they were at the beginning of the Anthropocene.

Acidification decreases the ability of the ocean to absorb additional atmospheric CO_2, which implies that future CO_2 emissions are likely to lead to more rapid global warming. Ocean acidification is also problematic because of its negative effects on marine ecosystems, especially marine calcifying organisms, and marine resources and services upon which human societies largely depend such as energy, water, and fisheries. For example, it is predicted that by 2100 around 70% of all cold-water corals, especially those in the higher latitudes, will live in waters undersaturated in carbonate due to ocean acidification. Recent research indicates that ocean acidification might also result in increasing levels of jellyfish in some marine ecosystems. Aside from direct effects, ocean acidification together with other global change-induced impacts such as marine and coastal pollution and the introduction of invasive alien species are likely to result in more fragile marine ecosystems, making them more vulnerable to other environmental impacts resulting from, for example, coastal deforestation and wide-scale fisheries.

The Marine Board-ESF Position Paper on the *Impacts of Climate Change on the European Marine and Coastal Environment – Ecosystems*[1] indicated that presenting ocean acidification issues to policy makers is a key issue and challenge. Indeed, as the consequences of ocean acidification are expected to emerge rapidly and drastically, but are often not well known or are completely unknown, a strategic workshop was organised by the ESF Standing Committee for Life, Earth and Environmental Sciences (LESC) in cooperation with the ESF EUROCORES Programme EuroCLIMATE. The aim was to address the issue of the impacts of ocean acidification on both the natural and socio-economic systems, and to identify the gaps of knowledge in this field. The present Science Policy Briefing resulting from this strategic workshop has undergone external international peer review and has been approved by both the Marine Board-ESF and LESC.

The ESF considers this Science Policy Briefing on the ***Impacts of Ocean Acidification*** an important step towards raising awareness amongst a wide range of research actors, policy makers and funding agencies. Taking into account the range of priorities and key areas of research requiring action at the pan-European level, a series of recommendations for European actions have been drawn up under the following five headings: (i) increase understanding and improve quantification of the organismal and ecosystem responses to ocean acidification; (ii) include the human dimension by increasing collaboration and integration efforts between natural and social sciences; (iii) rationalise, improve and focus monitoring and data gathering, management, processing and accessibility efforts; (iv) increase dissemination, outreach and capacity-building efforts, in particular related to communicating ocean acidification to stakeholders (policy makers, research funders, public, media, etc.); and (v) improve coordination of ocean acidification research and collaboration both at the national and international levels.

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Professor Reinhart Ceulemans, Chair, LESC
Mr. Lars Horn, Chair, Marine Board-ESF

Box 1: **Key Recommendations for European Actions**

Key recommendations for European actions in order to fully understand the impacts of ocean acidification are as follows:

1) quantify further the biological and biogeochemical responses to ocean acidification from the organismal to the ecosystem level
2) integrate natural and social sciences to help mitigate ocean acidification and develop adaptation strategies, taking into account the socio-economic impacts on natural resources and human communities. The full cost of abating CO_2 emissions, and of carbon capture and storage should be also considered
3) ensure adequate and sustainable monitoring of key marine ecosystems and environmental services
4) facilitate dissemination and capacity building to help deliver scientific knowledge-based advice to research funders and policy makers, to share best practices among researchers and success stories with the general public, and to raise the profile of this issue in future environmental change assessments
5) coordinate and strengthen European research on the impacts of ocean acidification, including sharing of research infrastructure, resources and knowledge.

> **“We, scientists who met in Monaco to review what is known about ocean acidification, declare that we are deeply concerned by recent, rapid changes in ocean chemistry and their potential, within decades, to severely affect marine organisms, food webs, biodiversity, and fisheries. To avoid severe and widespread damages, all of which are ultimately driven by increasing concentrations of atmospheric CO_2, we call for policy makers to act quickly to incorporate these concerns into plans to stabilize atmospheric CO_2 at a safe level to avoid not only dangerous climate change but also dangerous ocean acidification.”**
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> Extracts from the “Monaco Declaration”
> presented at the end of the Second Symposium on
> “The Ocean in a High-CO_2 World”, October 2008.

Introduction and rationale

Since the beginning of the industrial revolution the release of carbon dioxide (CO_2) from our industrial and agricultural activities has resulted in atmospheric CO_2 concentrations that have increased from approximately 280 to 387 parts per million (ppm). The atmospheric concentration of CO_2 is now higher than experienced on Earth for at least the last ca. 25 million years and is expected to continue to rise at an increasing rate. The ocean has absorbed about 430 billion tons of CO_2 from the atmosphere, or about one-third of anthropogenic carbon emissions[2]. This absorption has benefited humankind by significantly reducing greenhouse gas levels in the atmosphere, thereby minimising global warming. However, the pH (the measure of acidity) of ocean surface waters has already decreased by about 0.1 units, from an average of about 8.2 to 8.1 since the beginning of the industrial revolution[3]. By the middle of this century atmospheric CO_2 levels could reach more than 500 ppm, and by 2100 they could be well over 800 ppm (IPCC scenario B2, 2007). This would result in an additional mean surface water pH decrease of approximately 0.3-0.4 pH units by 2100, implying that the ocean would be about 100-150% more acidic than at the beginning of the industrial revolution.

When CO_2 is absorbed by seawater, chemical changes occur that reduce seawater pH and the concentration of carbonate ions in a process commonly referred to as ocean acidification. Carbonate ions are a basic building block of skeletons and shells for a large number of marine organisms, including corals, shellfish, and marine plankton. Some of these smaller calcifying plankton are important food sources for higher marine organisms. Thus ocean acidification could have profound impacts on some of the most fundamental biological and geochemical processes of the sea in coming decades. On the other hand, not all biological impacts from rising atmospheric CO_2 are necessarily deleterious for a species. Some species may even prosper. However, it is not known how these prospering species will impact the ecosystem or the biogeochemical cycles as a whole and whether they will sustain the ecosystem services currently provided by the food webs and ecosystems of today.

This rapidly emerging scientific issue of ocean acidification and its possible ecological and economical impacts (which are largely unknown or not quantified) have raised serious concerns across the scientific and fisheries resource management communities. Only very recently, the socio-economic consequences of ocean acidification have been started to be evaluated and comprehensive actions have been called for (see **Box 2**).

The motivation for this ESF Science Policy Briefing is that although global change and global warming have been topics of intensive research for more than a decade, ocean acidification has only recently been put on the research agenda[a]. Impacts of ocean acidification may be just as dramatic as those of global warming and the combination of both are likely to exacerbate consequences, resulting in potentially profound changes throughout marine ecosystems and in the environmental and socio-economic services that they provide to humankind (e.g., IPCC – Synthesis Report, 2007)[b].

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[a] Several recent initiatives and reports have addressed consequences of ocean acidification in natural environments. For instance, the *Symposia on the Ocean in a High-CO_2 World* (ioc3.unesco.org/oanet/HighCO2World.html), the *Impacts of Increasing Atmospheric CO_2 on Coral Reefs and Other Marine Calcifiers* workshop (www.isse.ucar.edu/florida), the IGBP-SCOR Fast Track Initiative on *Ocean Acidification – Atmospheric CO_2 and ocean biogeochemistry: modern observations and past experiences* (igbp-scor.pages.unibe.ch), the UK Royal Society report *Ocean acidification due to increasing atmospheric carbon dioxide* (royalsociety.org/displaypagedoc.asp?id=13539), the German Advisory Council on Global Change *Future Oceans – Warming Up, Rising High, Turning Sour* report (www.wbgu.de/wbgu_sn2006_en.pdf), the OSPAR *Effects on the marine environment of ocean acidification resulting from elevated levels of CO_2 in the atmosphere* report (www.ospar.org/v_publications/download.asp?v1=p00285) or the JRC IES *Marine and Coastal Dimension of Climate Change in Europe* report (ies.jrc.ec.europa.eu/documentation/scientific-reports/global-environment-monitoring-2.html). The recent issue of *Current – the Journal of Marine Education* on *Ocean Acidification – from Ecological Impacts to Policy Opportunities* (www.us-ocb.org/CurrentFINAL.pdf) present some of the latest findings in this field.

[b] The Intergovernmental Panel on Climate Change (IPCC, www.ipcc.ch) is a scientific intergovernmental body set up by the World Meteorological Organization (WMO) and by the United Nations Environment Programme (UNEP) to provide the decision-makers and others interested in climate change with an objective source of information about climate change. Its role is to assess the latest scientific, technical and socio-economic literature produced worldwide relevant to the understanding of the risk of human-induced climate change, its observed and projected impacts and options for adaptation and mitigation. The findings of the IPCC Assessment Reports (AR5 is currently under preparation) played a decisive role in leading to the United Nations Framework Convention on Climate Change (UNFCCC) and provided key inputs for the negotiations of the Kyoto Protocol in 1997 and its follow-up.

Box 2: **Key recent initiatives**

Ocean Acidification Network – International initiative developed by the International Geosphere-Biosphere Programme (IGBP), the Scientific Committee on Oceanic Research (SCOR), the UNESCO's Intergovernmental Oceanographic Commission (IOC) and the IAEA's Marine Environment Laboratories (MEL) as a follow-up of an IOC-SCOR symposium in 2004. This information network community provides a central source of information for ocean scientists on ocean acidification research activities. – www.ocean-acidification.net

Ocean Acidification blog – an information outlet on ocean acidification — oceanacidification.wordpress.com

United Nations Environment Programme (UNEP) World Conservation Monitoring Centre (WCMC), Ocean Acidification info page — www.unep-wcmc.org/resources/ocean_acid_promo.aspx

International Union for Conservation of Nature (IUCN) Coral Reef Resilience to Climate Change — www.iucn.org/cccr/resilience_to_climate_change/#2

International Coral Reef Initiative (ICRI) Recommendation on Acidification and Coral Reefs (2007) — www.icriforum.org/secretariat/japangm/docs/Reco_acidification_2007.pdf

Position Analysis: CO_2 emissions and climate change: Ocean Impacts and Adaptation Issues, the Australian Antarctic Climate & Ecosystems — Cooperative Research Centre. June 2008 — www.acecrc.org.au/drawpage.cgi?pid=publications&aid=797037

Honolulu Declaration on Ocean Acidification and Reef Management, August 2008, Hawaii, prepared by the IUCN and TNC, August 2008 — cmsdata.iucn.org/downloads/honolulu_declaration_with_appendices.pdf

Monaco Declaration (2008) calling for immediate action by policy makers to reduce CO_2 emissions sharply to avoid possible widespread and severe damage to marine ecosystems from ocean acidification, presented at the end of the Second Symposium on "The Ocean in a High-CO_2 World", October 2008, Monaco — ioc3.unesco.org/oanet/Symposium2008/MonacoDeclaration.pdf

Ocean Acidification – Recommended Strategy for a U.S. National Research Program, recently prepared by the US Ocean Carbon and Biogeochemistry Program, Subcommittee on Ocean Acidification, March 2009 — www.us-ocb.org/OCB_OA_Whitepaper.pdf

Research Priorities for Ocean Acidification prepared by Orr, J.C., Caldeira, K., Fabry, V., Gattuso, J.-P., Haugan, P., Lehodey, P., Pantoja, S., Pörtner, H.-O., Riebesell, U., Trull, T., Hood, M., Urban, E., and Broadgate, W. (January 2009) — ioc3.unesco.org/oanet/Symposium2008/ResearchPrioritiesReport_OceanHighCO2WorldII.pdf

Inter Academy Panel (IAP) statement on Ocean Acidification calls for world leaders to explicitly recognise the direct threats posed by increasing atmospheric CO_2 emissions to the oceans and its profound impact on the environment and society. June 2009 — www.interacademies.net/?id=9075

Ocean acidification and its impacts

Biological response

Continued CO_2 emissions could pose a threat to reproduction, growth, and survival at species level, and could lead to loss of biodiversity and profound ecological shifts. To date, little is known about such biological responses in the marine environment. By far, calcification is the process that has been the most thoroughly investigated[4,5]. For instance, shellfish or coral reefs may suffer directly from reduced growth rates. Yet very little is known regarding other processes relevant to understanding the full range of effects of ocean acidification. For some phytoplanktonic and benthic algae, carbon is not a limiting nutrient, whereas for others it is; for example, photosynthesis increases with increasing levels of CO_2. For finfish, direct impacts of ocean acidification may be limited. On the other hand, there are many unknowns: for balance and orientation finfish use calcareous structures in the inner ear (otoliths). How will otolith formation be affected or how will ocean acidification impair, directly or indirectly, the fertilisation success or developmental stages, particularly for indirect developers and broadcast spawners? For instance, salmon yearlings prey mainly on pteropods, which may be among the first organisms to be affected by ocean acidification. Hence, ocean acidification may influence the structure and productivity of primary and secondary benthic and planktonic production, which in turn may affect the productivity of fish communities and higher trophic levels. In addition, the interaction of ocean acidification with thermal tolerance may change the temperature-dependent biogeography for many fish species[6].

The relevance of CO_2, and more generally the carbon system, for organismal acid-base regulation is likely to be a key element in understanding the sensitivity of specific organisms to ocean acidification[7]. The mechanisms shaping sensitivity to long-term, moderate CO_2 exposures are insufficiently understood. Also, the regulatory, molecular and gene-expression mechanisms involved in acclimation and in limiting acclimation capacity are largely unexplored. At the organism level, CO_2 increases will cause shifts in tolerance ranges and adjustments in performance optima, capacities and limits.

Based on the presently-available data, little is known about the responses of genetically diverse populations, the life-history stages of animals and plants, synergistic effects from other stressors (e.g., temperature, hypoxia, nutrients), and the ability of organisms to undergo physiological and genetic adaptations to decreasing pH. A large gap in our understanding concerns the accumulation of responses from individual organisms to community and ecosystem levels. In view of these uncertainties, it is presently not yet possible to define critical thresholds (tipping points) for tolerable pH decline or to predict the pathways of ecosystem changes where threshold levels have been surpassed. In summary, our present knowledge of the effects of ocean acidification on marine biota is largely based on limited experimental work with single species and strains, maintained in short-term incubations, often exposed to abrupt and extreme changes in carbonate chemistry.

Aerial view of the Great Barrier Reef, one of the world's best protected and most fragile marine ecosystems.
Photo: ARC Centre of Excellence for Coral Reef Studies (AU)/Marine Photobank.

Biogeochemical cycles

The uptake of carbon by the ocean is determined both by the solubility of CO_2 and transfer of carbon to the deeper layers of the ocean by the biological carbon pump. The efficiency of the biological carbon pump relies on the relative amounts of carbon and calcium carbonate that are produced[8]. Although increased pCO_2 and high rates of organic carbon production would potentially result in a more efficient carbon pump, reduced ballasting by decreased calcium carbonate production, and thus reduced transfer of carbon to the deep sea, could make the biological carbon pump less efficient. Under increased ocean acidification, the efficiency of the combined physical and biological uptake will change, although the net direction of the change is unpredictable. On the one hand, the increased CO_2 inventory of the ocean will reduce its chemical buffer capacity. Under a "business as usual" scenario for CO_2 emission, this implies that the change in surface water dissolved inorganic carbon (DIC) per unit change in atmospheric CO_2 (mmol/kg/ppm) will be 60% lower in 2100 than today[9]. On the other hand, CO_2 fertilisation and changes in the microbial community structure might enhance the biological carbon pump[10]. The balance between these two counteracting processes are not known and although the organic carbon production may be enhanced, ballasting by carbonate shells and hence transport of carbon to the ocean interior might be significantly reduced.

Microbes (Protists, Bacteria, Archeae, Viruses) are the major drivers of important biogeochemical cycles (C, N, P, S, etc.). However, there is little understanding about how the microbial diversity responds to ocean acidification. Rising levels of CO_2 appear to increase nitrogen fixation and alter the elemental composition of planktonic communities. However, crucial knowledge about changes in biogeochemical cycles is lacking and, therefore, additional impacts on our future climate are unpredictable.

Changes in the global biogeochemical cycles operate on different time scales. Uptake of CO_2 and transport to the ocean interior is a rather rapid process (of the order of weeks to centuries). The effect of increased sedimentary carbonate dissolution (compensating ocean acidification) operates on intermediate timescales of the order of thousands of years. Ultimate recovery of the oceans from ocean acidification, however, is achieved only through weathering on timescales of millions of years[11].

Lessons from the past

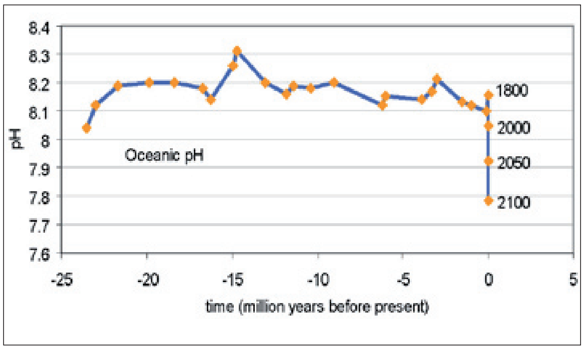
The effect of ocean acidification on the carbon system, its consequences for the ability of the ocean to take up carbon, its impact on marine ecosystems and the time involved in recovery of the ocean ecosystems has been investigated on a variety of time scales.

On a time scale of tens to hundreds of millions of years, the Paleocene-Eocene Thermal Maximum (PETM: ≈55 Myr ago) documents the global impact of ocean acidification[11]. During this period the benthic ecosystem experienced a massive extinction attributed to increased deep-sea anoxia. Ocean carbon models and sedimentary records show that chemical recovery from CO_2 emissions takes several thousand to a hundred thousand years, whereas biological recovery from past extinction events required millions of years. Input of CO_2 to the atmosphere during the PETM was of comparable magnitude to that of today's anthropogenic signal and happened on a time scale of less than 10000 years[12]. This makes these events the closest paleo-analogues for present-day ocean acidification — but importantly, the rate of change in today's event is most probably far more rapid.

On a glacial-interglacial time scale, changes in atmospheric pCO_2, known from ice cores, are mirrored by changes in foraminiferal shell weight[13]. This clearly shows a direct coupling between atmospheric CO_2, the oceanic carbon system, and biological responses (see also on similar principles operative during the Permian extinction[14]).

Measurements at time-series stations near the Canary Islands, Hawaii and Bermuda, as well as along repeated ocean sampling sections, confirm a 0.02 pH drop over the last decade[15,16,17] and corresponding decreases in saturation states of both calcite and aragonite, the main marine forms of carbonate minerals.

Projected acidification is likely to be stronger than has been experienced for tens of millions of years, and its rate of change is more than 100 times that found at any time during this period[18,19]. If CO_2 emissions continue



Past, contemporary and future variability of surface ocean pH. Turley et al. (2006)[17]

to rise at current rates, by the end of this century the resulting changes in seawater chemistry will expose many marine organisms to conditions that they may not have experienced during their entire evolutionary history[20]. The unknown outcome of this “Anthropocene experiment”[c] directly appeals to the application of the so-called “precautionary principle”[d].

The European dimension

Existing activities on ocean acidification have usually been initiated independently by individual scientists or groups with little overall coordination, resulting in a fragmented patchwork of projects. Therefore, there is an urgent need to coordinate present and future activities to avoid overlaps, to be cost-effective regarding investments and maintenance of expensive long-term sustained monitoring devices and experimental facilities and to stimulate cooperation within Europe and with communities worldwide.

Among the critical regions are those of high productivity and those which will be impacted first by large changes in the carbon chemistry[9]. Upwelling areas are particularly sensitive because lower pH water is brought to the surface[21]. Long time-series studies are not assured by any national or international institution or organisation. Adequate monitoring of European coastal and upwelling areas is lacking. The Mediterranean Sea is already under high anthropogenic and environmental pressure. As such, and because its coastal zone is extremely rich in calcifying organisms, it is a key region that might be particularly sensitive to ocean acidification effects. Other European marginal seas such as the North Sea and the Baltic Sea would also require continuous monitoring together with repetition of previous studies.

Europe is currently at the forefront of ocean acidification research. In June 2008, the EU FP7 Collaborative Project, EPOCA (www.epoca-project.eu), a consortium of 27 partners across nine European countries, received €6.5 million, was launched for 4 years to document ocean acidification and to investigate its impacts on biological and biogeochemical processes. A *Guide to Best Practices in Ocean Acidification Research and Data Reporting* currently prepared through EPOCA will be a milestone for this field. Although EPOCA involves many of the leading oceanographic institutions across Europe and more than 100 scientists and has a international scientific advisory committee and a stakeholders’ user group, this European effort is small relative to the challenge mankind is facing due to the future impacts of ocean acidification. In addition, there are emerging national programmes: for instance, the German, BMBF-supported project “Biological Impacts of Ocean ACIDification” (BIOACID, bioacid.ifm-geomar.de); the UK Collaborative NERC/Defra “Ocean Acidification Programme” (www.nerc.ac.uk/research/programmes/oceanacidification) and a few additional research efforts relevant to ocean acidification[e].

Yet, to maintain its leadership role, to understand the full implications of ocean acidification, especially in the current socio-economic context, and to influence what lies ahead, Europe must act now. No individual European member state is able to set up anything close to the large-scale research endeavour (combining natural and socio-economic sciences) that will be necessary to address and eventually tackle this challenge. Instead, Europe must take full advantage of the combined skills of its many member states by launching a large-scale concerted effort.

International context

Several major international research initiatives have markedly contributed to our knowledge of the ocean carbon cycle, the ocean circulation transporting carbon and other biogeochemically important elements, and how these might change in the future. National and international research initiatives on the effects of ocean acidification on organisms and ecosystems have already been started and are partly coordinated through international collaborative projects that have identified key research lines in relation to ocean acidification. The study of global marine biogeochemical cycles of micro-nutrients and of trace elements and their isotopes has helped to improve our understanding of how the cycles of other elements in the ocean – especially, N, P, Fe, Zn, Mn – affect the carbon

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c. “Anthropocene” is a term coined in 2000 by Nobel Prize winner Paul Crutzen that refers to the current period starting in the late 18th century when the industrial revolution and other human activities began to have a significant global impact on global climate and ecosystems.

d. European Commission: 2000, Communication of the Commission on the precautionary principle. COM (2000) 1; (renewed in its minutes, 20 Dec 2004; supported by the European Parliament, 2005).

e. Other relevant projects include: EU FP6 Integrated Project CarboOcean (www.carboocean.org), Marine Ecosystem Evolution in a Changing Environment (MEECE, www.meece.eu); EU FP7 Integrated Project Thermohaline Overturning – at Risk? (THOR, www.eu-thor.eu, to monitor and forecast the development of the N. Atlantic thermohaline circulation) Cold Ocean Acidification project (www.ipsl.jussieu.fr/~jomce/acidification); Biodiversity of Open Ocean Microcalcifiers (BOOM, www.sb-roscoff.fr/BOOM); Role of Pelagic Calcification and Export of Carbonate Production in Climate Change (PEACE, www.co2.ulg.ac.be/peace); Pelagic Ecosystem CO_2 Enrichment Study (PeECE, peece.ifm-geomar.de); UK Marine Climate Change Impacts Partnership: Annual Report Card, which includes acidification impacts and projections (www.mccip.org.uk/briefingsARC.html); and the US Ocean Carbon and Biogeochemistry program (OCB, www.us-ocb.org).

cycle. Future research activities on ocean acidification should build on such past projects[f], and extend current initiatives[g]. European research initiatives focused on ocean acidification should seek to contribute to these international projects, which depend on, and add value to, national research. This requires first that a specific database is produced within the European member states on their national activities with regard to ocean acidification.

The scenarios developed by the IPCC are critical for projections of the future trend of atmospheric CO_2 concentrations and for making predictions of ocean CO_2 uptake and changes in oceanic pH. Reciprocally, the fifth IPCC Assessment Report (AR5), which will be finalized in 2014, drastically calls for comprehensive studies of the carbon cycle, including the impacts of ocean acidification.

Continued observations (through research cruises, measurements from volunteer observing ships, and national time-series stations) of ocean carbon system parameters, from the surface to the deep sea, and integrated monitoring of the oceanic carbon cycle, worldwide and in specific locations are essential.

Fish are nowadays essentially an endangered resource under heavy management constraints. Recent trends in marine resources management aim to adopt an integrated ecosystem approach, including ecological, economic and social aspects. Impacts of ocean acidification on fisheries cannot, therefore, be understood without social scientists working on these management systems. The same holds true for commercially important shellfish species and coral reefs (fisheries, tourism and biodiversity conservation). Natural and social scientists as well as economists are just starting to collaborate to understand better the socio-economical impacts of ocean acidification.

Recommendations for European Actions

Critical unknowns should determine the agenda for developing mitigation and adaptation strategies for resources managers and policy makers. Actions may consist of the following items:

1) Quantifying the biological response to ocean acidification

Organismal and ecosystem responses

Since ocean acidification is an ongoing process taking place in a changing world, effects have to be studied in conjunction with other changing parameters. Therefore research requires experiments in mesocosms that address the issues of calcification, hypercapnia, temperature, salinity and anoxia. It will be essential to determine critical biological thresholds, adaptation and adaptive potential of taxa from different regions. Links between direct effects of ocean acidification at the organism level and indirect effects on food web structure and ecosystem functioning need to be understood.

Biogeochemical cycles

The interplay between microbial community changes, trace element speciation, carbon fixation and carbonate production determines the efficiency of the biological carbon pump. The effect of ocean acidification on all of these factors is at present virtually unknown. To estimate future changes in carbon uptake rate of the oceans, these factors need urgently to be better constrained. Laboratory, mesocosm and *in situ* experiments are essential to better understand ocean-acidification-related changes in microbial communities.

2) The human dimension; collaboration between natural and social sciences

In order to understand the impacts of future ocean acidification on human society, to mitigate further ocean acidification, and to develop potential adaptation strategies, social science in general and economic research in particular must become an integral part of an overall ocean acidification research agenda.

Two major human dimensions of ocean acidification have been identified:

A) **Implications of ocean acidification for the mitigation of climate change, including the additional global costs due the anticipated slow-down of the oceanic carbon pump induced by ocean acidification and the risks associated with sub-seabed carbon storage.**

Ocean acidification is expected to have a number of important implications for efforts to mitigate climate change, including increasing the cost of abating CO_2 emissions, risks associated with sub-seabed CO_2 sequestration, and to affect the design of policy instruments for controlling global environmental changes.

A slow-down of the oceanic carbon pump will affect the level of ocean acidification and would impose additional global costs in meeting a global CO_2 cap (as more CO_2 remains in the atmosphere). Under increased ocean acidification, the efficiency of the combined physical and CO_2 biological uptake will change, but the net direction of the change is as yet unknown. At present, the ocean removes about one-third of anthropogenic CO_2 emissions. A reduction in the capacity of this carbon sink would result in a larger CO_2 mitigation requirement to control climate change. The replacement cost of current CO_2 sequestration by the oceans (3 GtC/yr) is in the order

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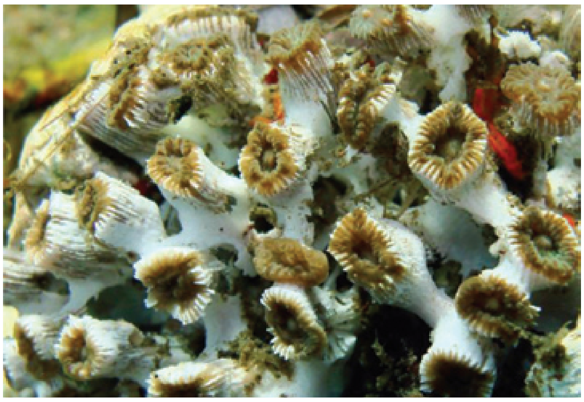
[f] Geochemical Sections (GEOSECS), Transient Tracers in the Ocean (TTO), Joint Global Ocean Flux Study (JGOFS), World Ocean Circulation Experiment (WOCE)

[g] Surface Ocean — Lower Atmosphere Study (SOLAS, www.solas-int.org), Integrated Biogeochemistry and Ecosystem Research (IMBER, www.imber.info), Land-Ocean Interactions in the Coastal Zone (LOICZ, www.loicz.org), Past Global Changes (PAGES, www.pages.unibe.ch), GEOTRACES project (www.geotraces.org), and the US Climate Variability and Predictability (CLIVAR) CO_2 Repeat Hydrography Program (ushydro.ucsd.edu). In addition, the International Ocean Carbon Coordination Project (IOCCP, www.ioccp.org) is a communication and coordination service for the ocean carbon community. It helps reaching international consensus on standards, best practices, data sharing, data syntheses, and continued development of the ocean carbon network.

Lophelia pertusa – a cold-water reef-forming coral that lives in deeper water — is widespread across all oceans and, with other calcareous organisms, is threatened by ocean acidification.
Photo: P.B. Mortensen, Institute of Marine Research (NO)



Endemic Mediterranean coral *Cladocora caespitosa* showing severe skeletal damage and dissolution due to ocean acidification.
Photo: Jason Hall-Spencer, Plymouth Univ.(UK)

of \$90-600 billion/yr, given expected future carbon credit prices of \$30-200/tCO_2. It should be recognised that a large-scale decrease in carbon uptake by the oceans represents a large shock to current climate change mitigation efforts and would require a major upward revision of GHG reduction targets, activities and costs.

A long-term mitigation strategy for climate change and ocean acidification is to limit future release of CO_2 to the atmosphere and/or enhance removal of excess CO_2 from the atmosphere. Carbon Capture and Storage (CCS) in geological formations (or sub-seabed) is now emerging as a technology that could contribute to reduce the future emissions of CO_2 to the atmosphere. While presenting a potential solution to climate change and ocean acidification, CCS also comprises the risk of leakage. In order to evaluate the severity of possible leaks from sub-seafloor CO_2 storage in the future (up to thousands of years into the future) there is a need to determine maximum biologically acceptable perturbations of the chemical environment on continental shelves. Insurance schemes for CCS require an observation and detection capability that would include leakage into the water column.[h]

For several reasons, ocean acidification has serious implications for the type of policy interventions required to control climate change. First, since ocean acidification is exclusively driven by CO_2, as opposed to climate change which is also caused by other greenhouse gases, the additional cost associated with CO_2 emissions due to ocean acidification changes the trade-offs between the reductions of greenhouse gases. Second, the absorption of CO_2 by the oceans and the impact of ocean acidification occur over a short time scale, whereas the warming of the atmosphere substantially lags behind the build-up of greenhouse gases in the atmosphere. This changes the dynamics of optimal emission control. Third, the consideration of ocean acidification also has implications for the choice of policy instrument for the control of climate change. Climate change may be countered by geo-engineering, but ocean acidification would continue unabated and may even accelerate if sulphur particles are used to cool the planet. Therefore, valuing the impact of ocean acidification will not only increase the estimates of the Pigouvian tax required to achieve efficient greenhouse gas emissions abatement[22], but it will affect other trade-offs and policies as well.

B) Socio-economic impacts: Economic and societal impacts of ocean acidification on fish, shellfish stocks and coral reefs, and related services.

Ocean acidification is expected to have impacts on several economically important marine resources, including fish stocks, shellfish, and coral reefs. Impacts on human societies will depend on the vulnerability, resilience and adaptation capacity of specific communities. The assessment of ocean acidification impacts should be conducted using a Total Economic Value framework, which considers use (direct and indirect) and non-use values of the resources damaged. It should be noted that socio-economic consequences of the combined impact of global warming and ocean acidification will probably become relevant before the possible damage of ocean acidification alone is fully expressed.

Direct impacts of ocean acidification on fisheries resources and the human communities they support are largely unknown. The total economic value generated by fisheries around the world comes from both capturing wild fish and from aquaculture. The combined value of wild capture and aquaculture is presently around \$150 billion/yr. Whereas some unknown fraction of the economic value of fisheries might be at risk from ocean acidification, other factors

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[h] The International Maritime Organization (IMO) Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention, www.londonconvention.org) was established to prevent pollution of the sea by dumping of wastes and other matter. Currently, 83 States are Parties to this Convention. In 1996, the “London Protocol” was agreed to further modernise the Convention and, eventually, to replace it. Under the Protocol all dumping is prohibited, except for possibly acceptable wastes on the so-called “reverse list”. The protocol allows storage of carbon dioxide (CO_2) under the seabed from 10 February 2007, thereby creating a basis in international environmental law to regulate this practice.

such as fishing pressure, co-determine the state of fish stocks. There is a need for multi-disciplinary research, linking marine biology and fisheries economics, to assess the scale of impacts to fisheries. Fisheries management models including the effect of ocean acidification should be developed.

A better understood consequence of ocean acidification is the reduction of calcium carbonate precipitation by shells of marine organisms, including commercially valuable shellfish, crustaceans and corals. The economic value of coral reefs is primarily linked to their function as a habitat and nursery for commercial fish stocks, acting as a natural barrier for coastlines, and for the provision of recreation and tourism opportunities. Assuming a conservative value[23] of \$100 000/km²/yr, the global economic value associated with reefs is in the order of \$30 billion/yr. Since ocean acidification is expected to impact a major part of these reefs within this century, it is plausible that the loss of coral reefs will amount to a loss of tens of billions of dollars per year. The economic value of damage to coral reefs due to ocean acidification has recently been estimated for the first time[24] and losses were found to be of the order of 0.18% of global GDP in 2100. This is one order of magnitude smaller than the estimated impact of climate change but still represents a substantial economic loss. Further research is required to refine these damage estimates and to extend the scope of analysis beyond coral reefs to other potentially impacted marine resources. Similarly, a recent case study of the evolution of US commercial fishery revenues, focusing especially on mollusks, indicated that substantial revenue declines, job losses, and indirect economic costs may occur due to ocean acidification, and proposed possible adaptation strategies designed to support fisheries and marine-resource-dependent communities, many of which already possess little economic resilience.[25]

An important aspect of these damage estimates is their distribution across populations, regions and countries. Economic losses from ocean acidification, like many other effects of climate change, fall disproportionally on the residents of developing countries. Fish provides more than 20% of the protein for more than 2.6 billion people (FAO estimates, 2007), but is much more important in the developing countries where people still rely on reef fisheries and shellfish collecting. Similarly, coral reefs are generally located in developing countries and provide important ecosystem services for poor coastal communities. Socio-economic research is required to assess the distributional consequences of ocean acidification and the impact on the livelihood of the poor.

The effect of ocean acidification on the global economy will depend on adaptations of the marine ecosystem as well as on human adaptation policies. Both are difficult to anticipate, making it difficult to calculate economic impact. A collaboration of natural and social sciences is required to research the potential for adaptation in both ecosystems and human systems, and the interplay between the two. The costs of adapting to ocean acidification need to be assessed.

Study of ocean acidification in offshore mesocosm CO_2 perturbation experiments. Photo: IFM-GEOMAR, DE

3) Monitoring and data requirements

Monitoring networks

It is highly recommended that all European marine sites, including those already in the European Ocean Observatory Network (EuroSITES, www.eurosites.info), act as oceanic carbon system data providers, which will include the North-East Atlantic and northern North Atlantic ocean areas from 20°N to 70°N, together with the Baltic, Mediterranean and North Seas. The “Implementation and Networking of large-scale long-term Marine Biodiversity research in Europe” project (BIOMARE, www.biomareweb.org), established under an EU FP5 programme, should also be incorporated since the diversity of European coastal ecosystems will likely show a similar diversity in responses to ocean acidification and it is coastal sites that generally provide most ecosystem services, for example, recreation, aquaculture, etc. These sites can be accessed through and are maintained by the MARS network of European Marine Institutes and Stations (www.marsnetwork.org). Existing long-time series should be maintained and new sensors and sampling/collecting devices should be developed. The biological pump should be monitored for changes in organic carbon and calcium carbonate production and export, as it has the potential to decrease oceanic natural carbon sequestration. Such data should then be contributed to, for example, CDIAC, part of the ICSU World Data Center for Trace Gases (cdiac.ornl.gov).

Geological perspective

Rates of change and magnitude of perturbations of the carbon system are still uncertain. Their quantitative reconstruction is essential to conclude from past ocean acidification events on the impact of ongoing ocean acidification. For instance, the *largest benthic biological extinction event* of the last ca. 100 Myr, the PETM, coincides with the largest global ocean acidification event. However, not only did the ocean become more acidic at this time interval but (bottom) water temperatures increased in parallel. It requires, therefore, targeted studies to unravel the roles that ocean acidification and hydrographic changes played in this mass extinction. Carbonate dissolution was not equally distributed worldwide during the PETM, although the exact geographical distribution is largely unknown. Since the impact of ocean acidification during the Eocene thermal maxima has been studied mainly in relatively deep (>1 km) settings, little is known from continental margins and marginal seas. It is still virtually unknown whether, and to what extent, ocean acidification affected calcifying organisms themselves.

4) Dissemination, outreach and capacity building

Communicating on ocean acidification to stakeholders (policy makers, funders, media, public, etc.) is important. Clear messages should be defined and used consistently across the sector, including confidence limits. A system should be put in place to share best practices and success stories.

A number of key stakeholders have been identified:

- **Communication to research- and potential industry-funders**
  Many research funding organisations are already aware of ocean acidification and are funding research in this area. However, they are not necessarily aware of the full spectrum of European activities in this area or the gaps in research. Therefore, European research relevant to ocean acidification is too fragmented and poorly coordinated. A strong effort by Europe to coordinate its own ocean acidification research would stimulate activities while enabling resources to be optimised by eliminating gaps and duplications. Equally important will be the social and economic consequences of ocean acidification, meaning that communication with the general public and all potential funders is crucial.
- **Communication to the climate change research community**
  Surprisingly, many researchers in climate change, including those working on mitigation and adaptation strategies, are unaware of many of the known implications of ocean acidification. The ocean acidification community has made in-roads to reach members of the global change community, who is not always fully aware of the impacts of ocean acidification (e.g., the IPCC fourth Assessment Report on Climate Change (2007), the Stern Report on the Economics of Climate Change, several scientific statements and declarations on ocean acidification, see **Box 3**). Impacts of ocean acidification should be included in all future climate change assessments. The certainty associated with ocean acidification, due to the simplicity of the chemical reaction of CO_2 and water, provides a powerful supplementary reason adding to the certainty of climate change.
- **Communication and Interactions with the international research community**
  It is recommended that the European ocean acidification community strengthens links with the international research community in order to stimulate research, share resources, and avoid needless redundancy; for instance, taking full advantage of PAGES, SCOR, GLOBEC, OCCC, the International Council for the Exploration of the Sea (ICES), the Marine Environmental Simulation Study for Future Projection of Marine Ecosystems (funded by the Japan Science and Technology Agency), the US Ocean Carbon and Biogeochemistry program (OCB) as well as some of the ongoing NSF-, NASA- and NOAA-funded, scientific activities, and a few research projects in Australia and New Zealand.
- **Communication to Stakeholders**
  In order to further address socio-economic implications, there is an essential need to establish two-way communication with stakeholders to better understand their problems and questions so that research can be properly designed and information conveyed in a useful manner. These stakeholders include fisheries and marine habitat managers, fishermen, community leaders, conservation groups, etc. Similarly communication with the media and the general public is also important.

5) Coordination

Coordination of ocean acidification research needs to address:

- coordination and collaboration of research programmes relevant at national level and at the regional level, taking into account the very different marine environments in Europe (Arctic, Baltic, North Sea, Mediterranean, Black Sea, North-East Atlantic) and of EU projects related to ocean acidification;
- coordination and collaboration at the international level of European activities with those outside Europe (e.g., United States, Japan, Korea, Australia, China). While coordination within Europe is underway, it will be important to integrate European activities with the global effort on ocean acidification research. European science (and the science of other countries) will benefit from such coordination, including stimulation of new ideas by bringing together scientific perspectives from around the world, sharing of physical resources (e.g., ships, mesocosms, new equipment designs), standardisation of protocols and instrumentation, possibilities for coordination of related national efforts to identify overlaps and gaps, and access to parts of the world where European scientists might benefit from other expertise and past experiences.

6) Final statement

Understanding the risks and consequences of ocean acidification and recognising that both ocean acidification and global warming are caused by anthropogenic CO_2 emissions will help to set in motion a stringent global change mitigation and adaptation policy in Europe and worldwide.

Ocean acidification is already occurring today and will continue to intensify, closely tracking global CO_2 emissions. Given the potential threat to marine ecosystems and the ensuing impact on human society and economy, especially as it acts in conjunction with ocean warming, there is an urgent need for immediate action. This “double trouble” of climate change and ocean acidification is arguably the most critical environmental issue that

Box 3: **European Policy Context**

European Integrated Maritime Policy

(ec.europa.eu/maritimeaffairs/subpage_en.html)
In October 2007, the European Commission presented its vision for an Integrated Maritime Policy (IMP) for the European Union in a Blue Book, providing the overall framework for policy areas related to the sustainable management of European marine waters, including environment and research. The IMP is the central policy instrument to develop a thriving maritime economy in an environmentally sustainable manner. The Action Plan that comes with the Blue Book introduces several actions which are directly or indirectly related to the issue of ocean acidification and greenhouse gas emissions, including actions on reduction of air pollution from ships, marine-based energy infrastructures and resources, and on mitigation and adaptation to climate change. It also considers Carbon Capture and Storage as a crucial element of European actions needed to meet the Community's climate change objectives to reduce impacts of things such as ocean acidification. To this end, the Commission proposed a Directive in January 2008 to enable environmentally-safe capture and geological storage of CO_2 in the EU as part of a major legislative package. The Directive was adopted by the Parliament and the Council in March 2009.

Thematic Strategy on the Protection and Conservation of the Marine Environment

(ec.europa.eu/environment/water/marine/index_en.htm)
The environmental pillar of the IMP, the Thematic Strategy on the Protection and Conservation of the Marine Environment, includes the Marine Strategy Framework Directive aiming to achieve good environmental status of the EU's marine waters by 2021 and to protect the resource base upon which marine-related economic and social activities depend. To this end, each Member State, in close cooperation with the relevant other Member States and third countries within a Marine Region, will be required to develop Marine Strategies for its marine waters. In the consolidated text of the Marine Strategy Framework Directive, pH and pCO_2 profiles or equivalent information used to measure marine acidification are mentioned as "physical and chemical features" which have to be monitored by Member States, and used to determine good environmental status.

European Strategy for Marine and Maritime Research

(ec.europa.eu/research/press/2008/pdf/com_2008_534_en.pdf)
The research pillar of the IMP is provided by the European Strategy for Marine and Maritime Research which was adopted by EC Communication in September 2008. It sets out a framework for defining the marine and maritime RTD needs and potential in Europe. The aim of the strategy is to propose the means to create a better integration between marine and maritime research while supporting infrastructure, education, capacity-building and a new cross-thematic approach. Climate change, impact of anthropogenic activities on marine and coastal ecosystems and the exploration of marine renewable energy sources are identified as major research topics requiring a cross-thematic approach.

European Climate Change Policy

(ec.europa.eu/environment/climat/home_en.htm)
The EU has been trying to address its own greenhouse gas emissions since the early 1990s with the first (2000) and second (2005) European Climate Change Programme (ECCP) and more recently the Climate Action and Renewable Energy Package (2008) to fight climate change and promote renewable energy up to 2020 and beyond. This package sets out the contribution expected from each Member State to meet these targets of reducing overall emissions to at least 20% below 1990 levels by 2020 and increasing the share of renewables in energy use to 20% by 2020. It also proposes a series of measures to help achieve targets. Central to the strategy is a strengthening and expansion of the Emissions Trading System (EU ETS), the EU's key tool for cutting emissions cost-effectively. Emissions from the sectors covered by the trading system will be cut by 21% by 2020 compared with levels in 2005. A single EU-wide cap on ETS emissions will be set, and free allocation of emission allowances will be progressively replaced by auctioning of allowances by 2020. The climate and renewable energy package also seeks to promote the development and safe use of Carbon Capture and Storage (CCS), a suite of technologies that allows the CO_2 emitted by industrial processes to be captured and stored underground where it cannot contribute to global warming.

In April 2009, the European Commission presented a policy paper known as a White Paper, "**Adapting to climate change: Towards a European framework for action**", which presents the framework for adaptation measures and policies to reduce the European Union's vulnerability to the impacts of climate change. It emphasises that decisions on how best to adapt to climate change must be based on solid scientific and economic analysis. The White Paper is accompanied by several working documents, one of which touches upon water, coasts and marine issues including ocean acidification.

humans will have to face in the immediate future. The impacts of ocean acidification will be global in scope yet they are some of the least understood of all global change phenomena. Within Europe are working some of the world's leading scientists who study ocean acidification. Their qualifications result in part from previous EU- and ESF-funded programmes, and hence these scientists are already accustomed to working together. Given that chemical effects are already measurable and that ecological impacts and thereafter the socio-economic impacts may be dramatic within only decades, Europe must now accept the challenge to stimulate and better coordinate its research on ocean acidification. The immediate effect will be for Europe to maintain its role as the world leader in this research field. Such a challenge is fundamental if one is to fully understand the consequences of and eventually help mitigate ocean acidification which, along with climate change, might turn out to be the most crucial environmental problem and socio-economic challenge of the century.

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