# Priorities for Research on the Ocean in a High-$CO_2$ World[1]

## Introduction

The atmospheric concentration of carbon dioxide is now higher than experienced on Earth for at least the last 400,000 years, if not the last several million years, and is expected to continue to rise, leading to significant global temperature increases by the end of this century. It is now well established that there is a strong possibility that surface ocean $pCO_2$ levels will double over their pre-industrial values by the middle of this century, with accompanying surface ocean pH changes that are 3 times greater than those experienced during the transition from glacial to interglacial periods.

Much discussion has been devoted to how to "sequester" some of the atmospheric carbon dioxide in plant biomass, in geologic structures,[2] or in the ocean. The ocean is absorbing approximately one-third of the carbon dioxide added to the atmosphere by human activities each year, and over the next few millennia, is predicted to absorb approximately 90% of the $CO_2$ emitted to the atmosphere, after atmospheric $CO_2$ concentrations are stabilized. The ocean is one of the largest natural reservoirs for carbon. Ocean strategies for sequestering atmospheric $CO_2$ involve enhancing the ocean's natural capacity to absorb and store atmospheric $CO_2$, either by inducing and enhancing the growth of carbon-fixing plants in the surface ocean, or by bypassing the slow, surface-to-deep water transfer of dissolved $CO_2$ by directly injecting it into the deep ocean. Although much relevant research has been conducted in the past decade, the potential effectiveness and risks of these forms of carbon sequestration in the ocean have not been thoroughly discussed and assessed. Even relatively small changes in $CO_2$ concentrations may have large, as yet not completely understood, impacts on marine life and natural biogeochemical cycles of the ocean. New research is necessary to gain a better understanding of how ocean biology and chemistry will operate in a high-$CO_2$ world, so that predictive models can include appropriate mathematical representations of these processes and accurate parameter values for monitoring and quantifying changes from the present ocean.

The Scientific Committee on Oceanic Research (SCOR) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO convened an open symposium on *The Ocean in a High-$CO_2$ World* on 10-12 May 2004 in Paris, France at UNESCO Headquarters. The symposium addressed the biological and biogeochemical consequences of increasing atmospheric and oceanic $CO_2$ levels, and possible strategies for mitigating atmospheric increases. Topics ranged from ocean physics, to chemistry and biology, including the impacts of elevated $CO_2$ levels on marine life, the dissolution of calcium

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[1] Information about the symposium—including the program, abstracts of plenary presentations and posters, summary documents about the meeting, and images can be found at http://ioc.unesco.org/iocweb/co2panel/HighOceanCO2.htm. SCOR and IOC will consider follow-up actions to the symposium, including consideration of the recommendations in greater depth. This material is based upon work supported by the National Science Foundation under Grant Nos. (0003700 and 0326301) to the Scientific Committee on Oceanic Research, as well as contributions from the Research Council of Norway and the Intergovernmental Oceanographic Commission of UNESCO.

[2] Geological storage in sub-seafloor formations poses potential risks for marine ecosystems also, if such reservoirs leak significantly, but this topic was not discussed in detail at the symposium.

carbonate, and the impacts on coral reefs. Speakers also evaluated the possible benefits and impacts of surface fertilization and deep-ocean $CO_2$ injection strategies. Symposium participants did not address whether it would be a good policy choice to sequester carbon dioxide in the ocean, but did identify what scientific information is available, and what is still needed, to make informed policy decisions.

The symposium included plenary presentations, discussion sessions on research priorities, and a poster session. To highlight some of the significant results from the symposium, a subset of results will be published in a special section of the *Journal of Geophysical Research--Oceans*. The papers in this special section will contribute to the work of the Intergovernmental Panel on Climate Change (IPCC) and to its Special Report on Carbon Dioxide Capture and Storage.

This report has been prepared to document research priorities that were identified in discussion sessions at the symposium for the benefit of ocean scientists and research program managers worldwide. The research priorities will be transmitted to the new international research projects (the Surface Ocean - Lower Atmosphere Study [SOLAS] and the Integrated Marine Biogeochemistry and Ecosystem Research [IMBER] project) for consideration, since both of these projects have major foci related to the ocean carbon cycle. (SOLAS and IMBER scientists participated in the symposium.) This report was prepared by the planning committee for the symposium and was reviewed by meeting participants and revised accordingly. Information about publication of this report in hard-copy version will be given on the symposium Web site.

## Discussion Groups

Following the plenary presentations, participants divided into three discussion groups. The groups met for two hours in individual sessions and met back in plenary session to report on their discussions and obtain feedback on their recommendations. All symposium participants had an opportunity to review this report and provide comments before it was finalized.

<u>High-$CO_2$ Group</u>
Chair: Ulf Riebesell
Rapporteur: Jean-Pierre Gattuso
Charge to Group: Identify research agenda/priorities related to the ocean in a high-$CO_2$ world, without mitigation, with attention to both biogeochemical and organismal/ecological aspects.

This discussion group identified priority research related to (1) forcing factors, (2) ecological/organismal aspects, (3) key biogeochemical processes, and (4) key types of ecosystems/species to be investigated.

1. Forcing factors

The most obvious forcing factor on the ocean in a high-$CO_2$ world is increased atmospheric $pCO_2$, which will increase the surface ocean (and eventually deep ocean) $pCO_2$ and lower pH. A major research priority will be to conduct research and modeling that will allow predictions of changes in ocean carbonate chemistry, and on how these changes will differentially affect calcitic and aragonitic organisms. As $pCO_2$ is increasing, other environmental variables will also change as a result. For example, likely changes that will accompany increased $pCO_2$ include increased temperature, changes in availability of nutrients (due to changes in redox conditions, ocean mixing, patterns of precipitation, dust inputs, and increased stratification), decreased $O_2$ in the warmer water, changes in salinity due to heating and precipitation effects, and changes in ocean mixing, circulation and wind. It will be very important to consider, in research, observational, and modeling activities, how these changes interact to affect marine biogeochemical processes and feed back to the Earth system. It also will be important to consider regional differences and to consider the combined effects of higher $pCO_2$ levels, higher temperature, and low $O_2$ concentrations.

2. Ecological/organismal aspects

Keeping in mind the forcing factors described above, it will be necessary to conduct research on both ocean biology and biogeochemistry. In terms of biology, effects are naturally expected for calcifying organisms, but it is also important to study the effects of increasing ocean $pCO_2$ and associated environmental changes on non-calcifying organisms. Interactions and synergies among variables (e.g., $pCO_2$ and temperature) are particularly important. Specifically, research should include

a. Effects on community structure and composition (including how species-specific responses will affect community composition), from bacteria to vertebrates
b. Effects on genetic diversity, species diversity, and the diversity of functional groups
c. Microevolutionary potential and rate of evolutionary change—Earth's temperature and atmospheric $CO_2$ concentrations have changed in the distant past, but not at the rapid pace that is now occurring, nor at the high $CO_2$ levels now encountered. Many organisms were probably able to evolve quickly enough to adapt to global changes in the past. Will they be able to adapt to the more rapid pace of change now occurring? Can adaptation occur under a continually and rapidly changing environment versus one that eventually stabilizes?
d. Sub-lethal effects—Most effects are likely to be sub-lethal, including decreased reproductive potential, slower growth, and increased susceptibility to disease.

3. Key biogeochemical processes

Increasing surface ocean $pCO_2$ and decreasing pH can affect a variety of processes that are important in regulating the oceanic cycles of carbon, nitrogen, and other elements. New research is needed to understand how the ocean will respond to increasing atmospheric $CO_2$, particularly related to

- Primary production—Will increasing $pCO_2$ in the surface ocean fertilize phytoplankton? If so, which species? What effects will this have on higher trophic levels? Since $CO_2$ generally is not a limiting resource for phytoplankton, production might not increase much, due to limitations in other elements. $CO_2$ fertilization may affect elemental stoichiometry (C/N/P).
- Remineralization—Auto- and heterotrophic processes are likely to respond differently to environmental changes (e.g., due to differences in temperature dependency). What effect will this have on the balance between primary production and remineralization?
- Will changes in nitrogen fixation, denitrification and nitrification be induced by changes in phytoplankton species composition and changes in oxygen levels?
- DOM transformations (aggregation, solubilization, biological turnover)—Will increasing $pCO_2$ change the proportion or type of carbon that enters the DOM pool? How will this affect the dynamics of dissolved organic material and particles?
- How does increasing $pCO_2$ impact the precipitation of $CaCO_3$ by planktonic and benthic calcifiers? What are the current dissolution kinetics of aragonite and calcite and how might they change under different scenarios of increased $pCO_2$? What impact will increasing $pCO_2$ and decreasing pH have on dissolution of $CaCO_3$ in the upper ocean, throughout the water column, and in ocean sediments? Will there be an impact on the $CaCO_3$ compensation depth?
- How will changes in the above processes affect export production and the rain ratio?

4. Key types of ecosystems/species to be investigated
Some ecosystems are more likely to be affected than others by increasing oceanic $pCO_2$ and decreasing pH, or may have more significant feedbacks to the Earth system. These ecosystems are priority areas for study:

- Ecosystems dominated by and/or structured by calcifying organisms such as coccolithophores, foraminifera, pteropods, and coral reefs (including different species and strains). There is some evidence that increasing $pCO_2$ would prevent the colonization of corals in new environments (within the temperature tolerance of the corals) because it will cause a decrease in the saturation of $CaCO_3$ in seawater.
- Ecosystems dominated by and/or structured by other biogeochemically relevant functional groups (pelagic and benthic) and "ecosystem engineers"/"keystone species"
- Intertidal and shallow subtidal areas
- The mesopelagic zone
- The Southern Ocean and subarctic Pacific Ocean

**Approaches**
Discussion group participants identified a set of promising approaches to study how the ocean might respond in a high-$CO_2$ world. These approaches range from small-scale laboratory experiments to open-ocean perturbation studies:

- Laboratory experiments—Small-scale studies in the laboratory can help isolate various factors to increase the understanding of results from larger-scale field studies and to guide planning for mesocosm and field studies.
- Mesocosm experiments—Experiments in mesocosm enclosures have produced useful results about how species composition changes in carbon-altered ecosystems. These experiments make it possible to create experimental designs with replication and controls on a larger scale and more realistic conditions than in the laboratory. An important activity will be to design standard experimental protocols that will make these experiments more reproducible.
- Short-term open-ocean perturbation experiments—Large-scale open-ocean iron fertilization experiments have yielded significant new knowledge about ocean ecosystems in the past decade. Short-term additions of carbon dioxide to various ecosystem types should result in similar information gains related to effects of carbon on the ocean.
- FACE-like experiments— Free Air $CO_2$ Enrichment (FACE) experiments are currently being conducted at many sites worldwide, in a variety of terrestrial, non-agricultural ecosystems. These experiments involve additions of carbon dioxide to research plots continuously for several years to maintain elevated atmospheric $CO_2$ levels that mimic levels that will be experienced under likely future scenarios. These experiments have demonstrated how plant communities will respond in both the short and long term. The continuity of these experiments is an important feature, because some long-term effects have been shown to differ from short-term effects on the same parameters. Both SOLAS and the IMBER project have proposed FACE-like experiments for the ocean. The benefit of such experiments is that they are more likely to show the actual long-term effects that will occur in the future. The major anticipated drawback is that it might be impossible to use for pelagic communities without enclosing them in some way or somehow using a Lagrangian approach. There is a need to start with a feasibility study because the amount of $CO_2$ or acid[3] required for a full-scale pelagic FACE experiment may be very high. The other drawback is the public perception problem. This drawback might be approached by pointing out that the effects of elevated $CO_2$ under "business as usual" scenarios may be so severe that understanding them might cause policymakers to think more carefully about emission controls or other mitigation methods.
- Model development— Ongoing development of models should be pursued, to assess the role of climate feedback and elevated $CO_2$ levels on ocean ecosystems and biogeochemistry. This will require the reconsideration of the distinction between the euphotic zone and the underlying waters (above the permanent pycnocline). Models should consider the high-$CO_2$ world in an Earth system context, where feedbacks and indirect effects are important and are often the dominant drivers, and disciplinary distinctions between functional

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[3] pH changes induced by $pCO_2$ changes occur without a change in alkalinity. pH changes induced by adding a mineral acid change alkalinity. Thus, changes in alkalinity must be considered in any experiments that change pH by adding acid.

biodiversity, ecosystem functioning and the fluxes of elements and associated feedbacks are no longer appropriate.

Other important research and observation approaches that should be explored include

- Encouraging experimentalists, field researchers, and modelers to work together
- Using specific locations that are acid- or $CO_2$-rich due to human effects or natural factors (e.g., the Rio Tinto, outlets of power stations, and natural $CO_2$ vents such as on Loihi Seamount)
- Adding stable pH sensors to Argo profiling floats
- Studying interactions between coastal areas and the open ocean, and between the seafloor and water column
- Following-up on the symposium with international working groups to focus on specific implementation tasks, though SOLAS and IMBER, the International Ocean Carbon Coordination Project, and/or SCOR working groups

Mitigation Group
Chair: Peter Haugan
Rapporteur: Andrew Watson
Charge to Group: Identify research agenda/priorities related to the effectiveness and environmental effects of mitigation approaches, with attention to both biogeochemical and organismal/ecological aspects.

The second discussion group was asked to identify research priorities related to ocean carbon sequestration science. The group discussed research related to the efficiency of sequestration and the potential environmental impacts of sequestration.

**Efficiency of sequestration**
Several important questions remain regarding the efficiency of ocean carbon sequestration. Answers to these questions will be necessary before an appropriate decision could be made about whether ocean carbon sequestration is technically feasible. Answers to some of these questions will require field experiments, some will require modeling experiments and some will require both. An important idea discussed was that ocean carbon sequestration techniques may be suitable in some places and times as “niche applications” among many others, starting with emission reductions.

$CO_2$ Injection—What is the long-term efficiency of storage of injected $CO_2$, depending on where (location and depth), when, and how the injection is done? Field experiments will probably require that tracers such as $SF_6$ be injected with the carbon, as there are many mixing and advection mechanism that might move the patch and global circulation models and finer-scale models may not now include the appropriate mechanisms. Other specific questions include

- What are the time and space scales of elevated carbon concentrations?

- When does the benthic boundary layer homogenize at sufficiently low carbon concentrations that further diffusion is reduced to a passive tracer problem?
- What are the mixing processes and time scales between the benthic boundary layer and ambient water?
- What is the response of $CaCO_3$ sediments to elevated carbon concentration?
- On the microscale, how do carbon dioxide hydrates form and dissolve?

Iron Fertilization—While participants agreed that iron fertilization experiments have been, and will continue to be, important in understanding natural systems and processes, all available research discussed at the symposium indicates that iron fertilization would be a very inefficient method of ocean carbon sequestration, from the viewpoint of the amount of carbon that could be sequestered by this method and the likelihood that even if iron limitations were eliminated, other nutrients and environmental factors would become limiting. Modeling should continue to assess likely effectiveness of iron fertilization, using information gained from continuing studies of the effects of iron added to the surface ocean.

**Impacts of sequestration**

$CO_2$ Injection—Midwater and deep water far-field effects of carbon injections need to be studied and modeled, since these will occur in 500 years or less. Long-term studies could be conducted in locations of restricted advection, such as fjords. Also, some deep-sea systems already experience low alkalinity and low oxygen, such as the Black Sea. Study of such natural systems could provide information about how other systems might change as alkalinity and oxygen levels decrease. Such comparisons are not perfect models, however, because the biological communities in natural areas have adapted over time and non-adapted communities might behave very differently in response to relatively sudden changes. Regions where the anthropogenic signal is already penetrating into the deep sea should also be a focus of study (e.g., some parts of the North Atlantic Ocean), since these are deep-sea regions where pH is already changing. What are the mechanisms of sub-lethal and lethal effects of $CO_2$? The effects of high $CO_2$ levels on deep-sea animals should be conducted under high pressures, at low temperatures, and in unsteady $CO_2$ conditions.

Iron Fertilization—To the extent that iron fertilization actually increases phytoplankton production, the fate of the increased phytoplankton biomass will determine the environmental effects of fertilization. Wherever phytoplankton biomass is remineralised by bacteria, bacterial respiration will use oxygen. Most models predict that any large-scale iron fertilizations in the Southern Ocean would drive most of the underlying water column hypoxic or anoxic, which would have substantial impacts on midwater and deep-sea organisms. It is possible that iron fertilization could increase the biomass of fish and higher trophic level organisms, but any such increases would need to be weighed against deleterious effects in other parts of the affected ecosystems. It will be important to study how iron fertilization as a sequestration technique would increase $N_2O$ production, cause extension of the anoxic regions, and/or change DMS production.

**Approaches**
This discussion group also recommended $CO_2$ perturbation experiments, at the seafloor where injections of $CO_2$ would occur. Such experiments could help us understand natural high-$CO_2$ ecosystems, which have been discovered in several locations in the deep sea (e.g., Loihi Seamount and in the Marianas Trench). These natural high-$CO_2$ areas could also be important study sites. A mid-water carbon injection experiment was also recommended, in which a patch of added $CO_2$ would be followed over time. Another important area of research would be to determine if the impacts of increasing $CO_2$ could be mitigated in specific key ecosystems. For example, would it be possible to artificially make the water over a coral reef more alkaline to protect the reef from negative impacts?

Education/Communication Group
Chair: Carol Turley
Rapporteur: Silvio Pantoja
Charge to Group: Identify (1) messages to convey, (2) audiences that need to receive the messages, and (3) mechanisms to convey the messages.

An important outcome of the symposium was the realization that the impact to the ocean of increasing atmospheric $CO_2$ has not been adequately conveyed to the general scientific community and the public. Therefore, one discussion group was formed to formulate a plan to communicate this important scientific information more widely.

**Message**
The message from the symposium must be consistent, objective, and based on sound science. The credibility of the scientific community and sponsoring organizations must be protected.

The core of the message is that human burning of fossil fuel is changing the chemistry of the ocean, increasing $pCO_2$ concentrations in the surface ocean and reducing the pH. These effects are already occurring and are measurable. These effects are in addition to and different from the effect of atmospheric $CO_2$ on global warming. The best scientific information available suggests that increasing oceanic $pCO_2$ and decreasing pH could have a significant negative effect on corals and other calcifying organisms, such as shellfish and some phytoplankton, disrupting marine food webs. One way to look at the future is that the ocean in a high-$CO_2$ world will be an "acidified ocean." It is important to convey to the public and policymakers that every bit of fossil-fuel $CO_2$ we can avoid emitting to the environment will help reduce these effects. Negative impacts on the ocean could be reduced through a range of mitigation approaches, including energy conservation, non-$CO_2$ producing energy sources, and non-ocean carbon sequestration approaches.

**Audience**
The first audience for a message about the rising $CO_2$ levels and associated acidification of the ocean is the scientific community, since even many ocean scientists at the meeting were not aware of the seriousness of the issue. The next audience for this message is policymakers and regulators, because they will need the information for good policy

decisions. Third, the general public needs to be informed that there is another impact of the increases in atmospheric $CO_2$, apart from global warming. Finally, this is a message that should be conveyed to college and high-school students, since their generation will experience greater impacts of today's government policies for carbon dioxide control than are already occurring.

**Mechanisms**

The message about surface acidification should be conveyed through a variety of mechanisms, to reach the different important audiences:

- The symposium planning committee should write a meeting report for *Science* or *Nature*, since these journals are widely distributed and reach scientists in other fields. Another potential venue would be *EOS*, to reach Earth scientists more specifically.
- The committee should also write a review article (e.g., for the News and Views section in *Science*) on ocean $p\mathrm{CO}_2$ and pH change promoted by increase of atmospheric $CO_2$
- The publication of scientific papers in *JGR—Oceans*. It is important to publish the science from the symposium in the peer-reviewed literature and to make it available for the IPCC process.
- IOC and SCOR staff should compile a contact list of experts available to speak with the press and policymakers.
- IOC and SCOR staff should create an image bank for the media, with the assistance of symposium participants.
- The Web page from the symposium (http://ioc.unesco.org/iocweb/co2panel/HighOceanCO2.htm) should be maintained as a vehicle to compile and make available information on this issue.
- Outreach through TV and other media should be considered.
- The communication strategy for this message should be broad.
- Funding resources will be needed for the above actions. SCOR, IOC, IGBP, GCP, and other interested organizations should be approached for financial resources.

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