SECOND INTERNATIONAL SYMPOSIUM ON

THE OCEAN IN A HIGH-CO_2 WORLD

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Report on

Research Priorities for Ocean Acidification

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1. Introduction

Fossil-fuel combustion releases carbon dioxide (CO_2) to the atmosphere, leading to a warmer climate. But there is another direct impact of increasing CO_2 in the atmosphere. It is changing the chemistry of the ocean.

The ocean absorbs CO_2 from the atmosphere at a rate of more than 20 million tons per day, thus removing one-fourth of the anthropogenic CO_2 emitted to the atmosphere each year (Canadell, 2007; GCP, 2008) and thereby reducing climate-change impacts of this “greenhouse gas”. But this benefit to humanity does not come without a cost to the ocean. When CO_2 dissolves in seawater, it forms carbonic acid. As this ocean acidification continues, it decreases both ocean pH and the concentration of carbonate ion, the basic building block of the shells and skeletons of many marine organisms.

Since the beginning of the Industrial Revolution, ocean acidity (defined here as the hydrogen ion concentration) has increased by 30%. This change is about 100 times faster than any change in acidity experienced during the last many millions of years. Within only a few decades, surface waters in the coldest parts of the ocean are projected to start becoming corrosive to the calcium carbonate shells of some marine organisms. But large unknowns, including the potential for organisms to adapt and the propagation of effects through ecosystems, need to be studied in order to evaluate ecological and economical impacts.

In May 2004, the Scientific Committee on Oceanic Research (SCOR) and the Intergovernmental Oceanographic Commission of UNESCO (UNESCO-IOC) co-hosted an international symposium, “The Ocean in a High-CO_2 World”, to evaluate what is known about these issues, as well as the potential benefits and impacts associated with proposed strategies to mitigate increasing atmospheric CO_2 concentrations by sequestering carbon in the ocean. This symposium brought together 120 of the world’s leading scientists from 18 countries with expertise in marine biology, chemistry, and physics in order to piece together what was known about the impacts of ocean acidification on marine ecosystems and to identify the research priorities needed to understand the mechanisms, magnitude, and time scale of these impacts. The journal *Nature* recently referred to this symposium as “a turning point in expanding awareness among scientists about acidification” (Goldston, 2008). Following this symposium, several national and international organizations requested SCOR and IOC to keep this issue under review, and their governing bodies agreed to make this symposium a regular event to be held every 4 years.

The 2nd symposium on *The Ocean in a High-CO_2 World* was held during 6-9 October 2008 at the Oceanography Museum of Monaco under the High Patronage of His Serene Highness Prince Albert II. The symposium was again sponsored by SCOR and IOC as well as the International Atomic Energy Agency’s Marine Environment Laboratories and the International Geosphere-Biosphere Programme. Additionally, it was supported financially by the Prince Albert II Foundation, the Centre Scientifique de Monaco, the U.S. National Science Foundation, the International Council for the Exploration of the Sea, the North Pacific Marine Science Organization, the Oceanography Museum, and the Monaco Government.

The meeting brought together 220 scientists from 32 countries to assess what is known about the impacts of ocean acidification on marine chemistry and ecosystems, covering 9 themes: future scenarios of ocean acidification, effects of changes in seawater chemistry on nutrient and metal speciation, paleo-oceanographic perspectives, mechanisms of calcification, impacts on benthic and pelagic calcifiers, physiological effects from microbes to fish, adaptation and microevolution, fisheries and food webs, and impacts on biogeochemical cycling and feedbacks to the climate system. The symposium also addressed acidification issues related to intentional sub-seabed storage of CO_2, impacts on economics, and links with policy. The symposium included invited and contributed talks, posters, and three discussion sessions: 1) natural and artificial perturbation experiments to assess acidification; 2) observation networks for tracking acidification and its impacts; and 3) scaling organism-to-ecosystem acidification effects and feedbacks on climate.

As a follow-up, results from this 2nd symposium are being disseminated via four documents: (1) a *Research Priorities Report*, (2) a *Summary for Policymakers*; (3) a *Conference Declaration*; and (4) a special issue of the peer-reviewed journal *Biogeosciences,* offering a subset of the contributed research papers. This document is the *Research Priorities Report*, which highlights the new findings and details the research priorities that were identified by the symposium participants during the discussion sessions. It was prepared by the symposium's international planning committee, and it is intended for ocean scientists and research program managers throughout the world.

2. Science Summary

Anthropogenic ocean acidification is rapid in the context of past natural changes. Surface ocean pH has already dropped by 0.1 units since the beginning of the Industrial Revolution, which is equivalent to a 30% increase in hydrogen ion concentration (referred to here as acidity). This rate of acidification has not been experienced by marine organisms, including reef-building corals, for many millions of years. The future chemical changes that will occur in the ocean as a result of increasing atmospheric CO_2 are highly predictable. Across the range of IPCC SRES scenarios, surface ocean pH is projected to decrease by 0.4 ± 0.1 pH units by 2100 relative to preindustrial conditions (Meehl et al, 2007). A previous natural ocean acidification event that occurred approximately 55 million years ago at the Paleocene-Eocene Thermal Maximum (PETM) is linked to mass extinctions of some calcareous marine organisms (Zachos et al., 2004). After the PETM's relatively rapid onset of acidification, which could have lasted for many centuries or millennia, it exhibited a slow recovery period that spanned millions of years. Today's anthropogenic "acidification event" differs because it is human-induced and because it may be occurring much more rapidly. Previous natural acidification events may have been associated with the five major coral mass extinction events that are known to have occurred during Earth's history (Veron, 2008). Recovery from the current large, rapid, human-induced perturbation, if left unchecked, will require thousands of years for the Earth system to reestablish even roughly similar ocean chemistry (Archer, 2005; Montenegro et al., 2007; Tyrrell et al., 2007; Archer and Brovkin, 2008), and from hundreds of thousands to millions of years for coral reefs to be reestablished, based on past records of natural coral-reef extinction events (Veron, 2008).

Ocean acidification is already detectable. Time-series records of ocean carbon chemistry over the last 25 years show clear trends of increasing ocean carbon and increasing acidity (decreasing pH) that follow increasing atmospheric CO_2 (Bates et al., 2007). These trends correspond precisely with what is expected from basic marine chemistry (Caldeira et al., 2007). Over the last two decades, there have also been measurable decreases in the shell weights of Southern Ocean pteropods (Roberts et al., 2008) and foraminifera (Moy et al., 2008) while corals on the Great Barrier Reef have shown a recent decline in calcification (Cooper et al., 2008). However, more studies are needed to verify that these declines in shell weights are due to ocean acidification.

Severe biological impacts may occur within decades. Projections of the saturation levels of aragonite (a metastable form of calcium carbonate used by many marine organisms) indicate that calcification rates in warm-water corals may decrease by 30% over the next century (Gattuso et al., 1998; Langdon and Atkinson, 2005). By the middle of this century, calcification rates of many warm-water corals are expected to drop to the point that they will be outpaced by erosion (Erez, 2008; Gattuso, 2008a; Manzello et al., 2008, Langdon et al., 2008), which would have serious impacts on coral reef ecosystems. Cold-water corals, which are found in deep waters, may also be in danger. These corals serve as habitat for many commercial fish stocks, and today virtually all of them are bathed in waters that are supersaturated with respect to aragonite. Yet by 2100, it is projected under the IS92a scenario that about 70% of these cold-water corals will be exposed to waters that are undersaturated with respect to aragonite, which would be chemically corrosive to their skeletal material (Guinotte et al., 2006). In manipulative experiments with cold-water corals, when ambient pH was reduced by 0.15 and 0.3 units, calcification rates declined by 30 and 56% (Maier et al., 2008). Some coastal waters in the Northeast Pacific have recently become undersaturated with respect to aragonite during spring due to upwelling onto the continental shelf of intermediate waters enriched in anthropogenic CO_2 (Feely et al., 2008). Off Iceland, invasion of anthropogenic CO_2 is causing deep waters to undergo this same transition to “corrosive” conditions, from being saturated with respect to aragonite to being undersaturated to the extent that every day, 1 km^2 more of seafloor is exposed to these conditions, as are associated bottom-dwelling organisms (Olafsson et al., 2008). This transition to undersaturated conditions is projected to occur within decades in surface waters over much of the polar oceans (Caldeira and Wickett, 2005; Orr et al., 2005; McNeil and Matear, 2008; Orr et al., 2008).

Marine organisms exhibit a range of responses to ocean acidification. Studies of marine calcifiers indicate that most but not all of them exhibit reduced calcification with increased ocean acidification (Fabry et al., 2008). Marine calcifiers differ because they have different mechanisms that control their internal microenvironment where calcification takes place. Also, different life stages of marine calcifiers respond differently. These differences need to be taken into account when designing experiments to evaluate likely future changes in calcification rates due to ocean acidification. The majority of sensitivity experiments have been carried out on adults of a limited number of species using short-term experiments. Studies are now examining the different life-cycle stages of organisms to identify which ones will be affected most severely. Early life stages may be particularly sensitive to acidification. For example, ocean acidification negatively affects sea urchin reproduction by reducing sperm motility and swimming ability, lowering fertilization success, and impeding embryo and larval development (Havenhand et al., 2008). One oyster species that was selectively bred to resist disease has been shown to be more resistant to acidification impacts (Parker et al, 2008), which raises the hope that under the right circumstances some organisms might be able to adapt to some degree. In contrast, longer experiments with calcifying phytoplankton, coccolithophores, indicate no adaptation to high CO_2 after even after 150 generations (Müller et al., 2008). Meanwhile, there is an open debate about the potential effects of acidification on coccolithophores (Riebesell et al., 2008; Iglesias-Rodriguez et al., 2008). Elevated CO_2 from ocean acidification affects a suite of physiological mechanisms (Pörtner, 2008). Effects of ocean acidification on ecosystems may occur first and be strongest where marine species are already stressed by anthropogenic warming. Physiological studies support the development of a cause-and-effect understanding for phenomena ranging from performance changes in individual species to changes in species interactions and phenologies at ecosystem levels (Pörtner and Farrell, 2008).

Naturally low pH environments provide a glimpse of ecosystems in a high-CO_2 world. Insights into how ecosystems may adapt to a high-CO_2 environment have been gained from natural environments near seafloor vents that emit CO_2 at ambient temperature as well as in regions with naturally varying pH gradients, such as coastal upwelling systems. The high-CO_2, shallow, seafloor vent areas around Ischia, Italy, in the Bay of Naples show that when mean pH conditions reach values that are expected for the end of the century, there is a total absence of some species, generally reduced biodiversity, and regime shifts to completely different ecosystems, where sea grasses and invasive species thrive (Hall-Spencer et al., 2008). Living gastropods also show severe eroding and pitting of shells in areas when average pH declines to 7.4 or less. There is a substantial decrease in species abundance in this area before mean pH drops below 7.8. Another case is the warm-water coral reefs that are found in naturally high-CO_2, low pH waters of the eastern tropical Pacific, which are less cemented and more prone to bioerosion (Manzello et al., 2008).

3. Socioeconomic and policy perspectives

Ocean acidification may affect fisheries, tourism, and stabilization of atmospheric CO_2. Effects of ocean acidification may propagate from individual organisms up through marine food webs, which could affect the multi-billion dollar commercial fisheries and shellfish industries as well as threaten protein supply and food security for millions of the world's poorest people. Coral reefs generate billions of dollars through tourism each year and serve as habitat for one-fourth of the world's fish species during at least part of their lifetime. Unfortunately, coral reefs appear particularly vulnerable because of the combined impacts of coral bleaching, caused by increased water temperatures, and ocean acidification, which will reduce calcification and weaken reef structure. With the development of carbon markets and international agreements to cap CO_2 emissions, a price tag can now be assigned to the acidification-driven degradation of the ocean's large capacity to absorb CO_2. With the carbon market price range of US$20 to $200 per ton of carbon, the ocean's current annual capacity of 2 gigatons of anthropogenic carbon per year represents an annual subsidy to the global economy of 40 to 400 billion dollars, which is about 0.1 to 1% of the global gross domestic product (Held, 2008). The ocean's capacity to take up anthropogenic CO_2 is being degraded by ocean acidification, which will make it more difficult to stabilize atmospheric CO_2 concentrations.

Costs of stabilizing atmospheric CO_2 much lower than inaction. Conventional wisdom of climate economics previously held that it would be too costly to mitigate greenhouse gas emissions to reach a target of 450-ppm CO_2 equivalents (CO_2e) (Nordhaus and Boyer, 2000). Unfortunately, stabilizing greenhouse gases at that level still runs a 54% chance that the anthropogenic increase in global-mean temperature will surpass 2˚C (Meinshausen, 2006). However, more recent economic analyses are more optimistic about how innovation spurred by investments in low-carbon technologies will reduce costs. A suite of carbon cycle-economy models predict the cost of pursuing the 450-ppm CO_2e target to be about 0.5% of the world GDP (Edenhofer et al., 2006). Sir Nicholas Stern estimates that the cost to attain the same 450-ppm level would be about 2% of world GDP (Stern [2006] estimates updated in June 2008). Similar estimates also are provided by the recent report to the Australian government (Garnaut, 2008). These costs are considered tolerable by most economists and are much smaller than would be those associated with inaction.

Achieving stabilization will require urgent, unprecedented cuts in global emissions. Although economically feasible when viewed over several decades, stabilising at even 650 ppmv CO_2e (roughly 530 ppm CO_2) would require that CO_2 emissions peak by 2020 and then be reduced, immediately, at a rate of 3% per year, which is equivalent in magnitude to the present rate of increase (Anderson and Bows, 2008). Such unprecedented cuts in global emissions will require swift implementation of ambitious international agreements complemented by local, regional, and national initiatives that lead the effort to meet this challenge early on and then go beyond.

Decision-makers need science-based policy advice. Scientific research formulates and answers scientific questions. But these answers may be far removed from what is needed by policymakers. In order to ensure the relevance, usefulness, and dissemination of results from acidification research, it needs to be formulated with policymakers considered as critical end-users. For ocean acidification research projects, the associated *user groups* should include policy experts with interests that span the relevant environmental, industry, and conservation sectors. These users should advise research scientists about what types of analyses and products would be most useful to managers and decision-makers, what format and nature the policy-related messages should take, and what are the best ways to disseminate results. These special users should also strive to integrate the resulting scientific findings into their own sector and organizations. An example of this type of group is the *Reference Users Group* of the European Project on Ocean Acidification (see http://www.epoca-project.eu).

4. Discussion Group Reports

Following the invited and contributed oral presentations, which were all held in plenary session, symposium participants divided themselves into three separate discussion groups. Each group met for 2 .5 hours and then returned to the final plenary sessions to report back on group discussions, make recommendations, and promote questions and further discussion. These three groups addressed perturbation studies, observational networks, and scaling up results and climate feedbacks.

Discussion Group 1: Natural and artificial perturbation experiments to assess acidification

Chair: Ulf Riebesell (IFM-GEOMAR, Kiel, Germany)
Rapporteur: Steve Widdicombe (Plymouth Marine Laboratory, UK)

Group 1 was asked to consider the following questions:

a. What experiments have been most useful to understand the potential effects of ocean acidification?
b. What have been the limitations in previous perturbation experiments?
c. How can these limitations be overcome?
d. What new perturbation experiments would help us better understand ocean acidification and its effects on fisheries and ecosystems?

Approaches

The group discussed the range of natural and artificial perturbation approaches that have been used to assess ocean acidification impacts. The discussion covered a range of paleoceanography studies, spatial variability studies, and use of mesocosms and modeling. These studies include

- Highly (or fully) controlled single-species laboratory experiments to look at species responses, to improve understanding of physiological mechanisms, and to identify longer-term, multi-generational, adaptation responses;
- Microcosms and mesocosms to elucidate community responses and to validate and up-scale single-species responses;
- Natural perturbation studies from CO_2 venting sites and naturally low pH regions such as upwelling regions, which provide insights to ecosystem responses, long-term effects, and adaptation mechanisms in low-pH environments;
- Manipulative field experiments; and
- Mining the paleo-record to develop and test hypotheses.

While many of these approaches for ocean acidification research are new and there are currently no common guidelines for best practices, scientists agreed that even “mistakes” in applying these approaches have increased our understanding of the mechanisms of organism and community response.

Limitations

One of the greatest current limitations is the lack of comparability among experiments. There is often insufficient description of the carbonate system parameters or other environmental conditions. Experiments use different pH scales, and the scale that is used is often undocumented. There is inadequate information about animal condition and there are problems when experiments are carried out with stressed animals. There are discrepancies between the use of wild and cultured specimens, and differences in practices of pre-acclimation, where an organism is slowly acclimated to the stressor rather than responding to sudden exposure. For paleo-studies, a significant limitation is the mismatch between paleo and modern ecosystems.

Other limitations include difficulties with experimental approaches and lack of coordination or agreement on methods, protocols, and data reporting, such as

- Problems with reproducibility of observations;
- Organisms that have been kept in culture for many years have been used for experiments, but may no longer be representative of natural populations, a problem that is well-known in human cell cultures;
- Experiments are limited to those species that are easy to maintain in the laboratory, thus ignoring many sensitive species;
- Studies have examined a single process (e.g., respiration, calcification, growth, etc.) without considering the integration of changes in multiple processes into the whole-organism response to high CO_2;
- Ecological processes are not sufficiently studied, including the importance of vulnerability at different life stages of the organisms, competition, and trophic interactions;
- Difficulties with maintaining natural conditions (e.g., food supply, densities) are prevalent;
- Investigators often report observations rather than try to identify the mechanisms responsible;
- Differences in perception of what makes a good or publishable result affects what is published, whereas the community also needs to hear about “mistakes” and conditions that produced no significant effects, so that we can learn from them;
- Dissemination of results and conclusions has been slow; and
- Communication among disciplines has been limited at best.

Overcoming limitations

To overcome many of these limitations, the group highlighted the importance of three key aspects: improved collaboration, increased funding, and greater public awareness.

Collaboration is needed to optimize limited resources, highlight common priorities, and facilitate greater data and information sharing. Several current technological limitations may be overcome through closer collaboration with engineers. Material from experiments, such as tissue or shell samples, should be shared more readily. Agreements on standards and best practices are needed, including the type of metadata that must be reported. Facilities and groups with expertise in mesocosms, laboratory manipulations, or particular analytical techniques should be identified to facilitate sharing of both expertise and facilities. Working groups on key organisms should be organized to review current knowledge and develop best practices for experiments. Communication is a key tool for overcoming many of the current limitations, and an effort should be made to announce experiments long in advance in order to encourage collaboration and ensure that other researchers from different disciplines can benefit from experimental material or data. A calendar of upcoming acidification experiments should be developed and maintained; associated Web sites should be improved to provide comprehensive information on ocean acidification activities.

Efforts to improve public awareness are crucial to overcoming limitations in ocean acidification research as well as funding. One suggestion is to identify several charismatic species that could serve as “acidification ambassadors” in museums, aquaria and schools, with experiments and videos explaining ocean acidification and its potential impacts on marine life.

New and improved experiments

Group 1 discussed needs for new types of experiments and approaches as well as the needs for improving and enhancing current approaches. Suggestions include to

- Develop an approach to link pelagic and benthic mesocosm studies;
- Improve the links between physiologists, ecologists and fisheries scientists to begin to look at integrated food webs;
- Enhance benthic and pelagic mesocosms and Free-Ocean CO_2 Enrichment-type systems to scale up and validate laboratory experiments;
- Carry out long-term perturbation studies to look at adaptation and microevolution;
- Apply a whole-organism approach with multiple end points, both physiological and behavioral;
- Improve methods to understand underlying mechanisms of calcification for different species;
- Study simple assembled “ecosystems” with multiple trophic levels to assess biological interactions and fluxes among organisms and across trophic levels;
- Develop an approach to study community-level responses by identifying simple communities that could be manipulated ;
- Assess what makes some species more tolerant to low-pH, high-CO_2 environments, and identify indicators of vulnerability and tolerance; and
- Develop and enhance the use of open-ocean mesocosms.

The group also discussed the potential for carrying out mesoscale, *in situ* CO_2 enrichment experiments, but repeatedly questioned the scientific value and data return of this approach relative to the large amount of funding that would be required to implement it. Finally, the group discussed the trade-off between the desire for perfect experimental results and the urgency of informing society and policymakers in order to influence CO_2 mitigation efforts.

Discussion Group 2: Observational networks for tracking acidification and its impacts

Chair: Toby Tyrrell (National Oceanography Centre, Southampton, UK)
Rapporteur: Chris Sabine (NOAA/PMEL, USA)

Group 2 was asked to consider the following questions:

a. How can we monitor changing chemistry (environments, sensors, networks, etc.)?
b. How can we detect impacts on calcifiers (techniques, variables, environments, etc.)?
c. How can we detect impacts on other organisms, ecosystems, and fisheries?
d. How do we optimize monitoring efforts to enhance our understanding of ocean acidification?

Tracking acidification and its impacts requires large-scale and sustained programs of *in situ* measurements. Participants stressed the need for early international cooperation to develop a coordinated, global network of ocean observations that could leverage existing infrastructure and programs as far as possible, while noting the need for additional sites for monitoring and process studies aimed explicitly at ocean acidification.

Key recommendations for future research are to

- Develop new instrumentation for autonomous measurements of CO_2 system parameters, particulate inorganic (PIC) and particulate organic carbon (POC), and other indicators of impacts on organisms and ecosystems;
- Maintain, enhance, and extend existing long-term time series that are relevant for ocean acidification;
- Establish new monitoring sites and repeat surveys in key areas that are likely to be vulnerable to ocean acidification;
- Develop relaxed carbon measurement methods and appropriate instrumentation that are cheaper and easier, if possible, for high-variability areas that may not need the highest measurement precision;
- Establish a high-quality ocean carbon measurement service for those unable to develop their own measurement capabilities;
- Establish international collaborations to create a data management and synthesis program for new ocean acidification data as well as data mining and archival for relevant historical data sets;
- Work on developing an ocean acidification index (perhaps saturometry using a standard carbonate material); and
- Initiate specific activities for education, training, and outreach.

One of the key questions regarding responses to ocean acidification is resolving the distinction between “tipping points” and adaptation. Are there geochemical thresholds for ocean acidification (e.g., $CaCO_3$ mineral solubility) that, if crossed, will lead to irreversible deleterious effects on species or ecosystems (i.e., tipping points)? Or are organisms or ecosystems sufficiently elastic that adaptations to changing seawater chemistry will occur that will reduce potential negative impacts of ocean acidification? Ocean acidification-relevant indicators beyond basic water-column carbonate chemistry have yet to be adequately developed. Routinely measurable parameters that reliably detect biotic effects of ocean acidification, such as indicator-species abundance, calcification per cell, biochemical signatures of physiological stress, or ecosystem species composition, do not yet exist but need to be developed and incorporated into a global monitoring network.

Technical Needs

Workshop participants agreed that it is essential to promote the use of standardized measurement protocols and data reporting guidelines for ocean acidification research. An internationally agreed-upon guide to best practices for carbon measurements was recently published (Dickson et al., 2007), but other ocean acidification measurements also need to be standardized. The group also thought that a set of relaxed criteria could be developed for making carbon measurements easier and cheaper, for cases that do not require the currently recommended high precision and accuracy. However, it was agreed that the uninformed use of cheap, 'off-the-shelf' pH sensors should be discouraged for most ocean acidification-related purposes, because high-quality results are unlikely to be obtained. Group 2 recommends that for shipboard measurements of the inorganic carbonate system, the two parameters that should be measured are total dissolved inorganic carbon and total alkalinity, because certified reference materials (CRMs) currently exist for both (http://andrew.ucsd.edu/co2qc/), whereas no CRMs exist for the other parameters.

Currently, pCO_2 and pH sensors are available for stationary platforms and underway shipboard measurements. Workshop participants emphasized the vital importance of developing autonomous systems for measurement of additional parameters of the seawater CO_2 system, particularly total dissolved inorganic carbon and total alkalinity. Because pCO_2 and pH strongly co-vary, they are not the ideal pair of parameters to measure. Additionally, experimentalists voiced a strong need to develop new methods to quantify the inorganic carbon system in seawater using small-volume samples (5 to 20 ml).

Field Observations

Existing infrastructure and monitoring programs should be leveraged as far as possible. Programs that already monitor organisms or ecosystems could be expanded to also monitor ocean acidification by adding carbonate chemistry measurements. For example, additional measurements and process studies could be conducted at Long-Term Ecological Research sites such as those in the California Current or near Palmer Station in the Western Antarctic Peninsula. Although ship-board surveys will likely be the primary approach for making coordinated multi-disciplinary ocean acidification studies, autonomous sensors on moored buoys and gliders should be used extensively to enhance the global network. For example, carbon sensors should be mounted on the OceanSITES network of moorings. Yet new monitoring sites, process study sites, and surveys, will still be needed in high-sensitivity regions that are critical for understanding ocean acidification. This may be accomplished through the development of regional networks. Satellite algorithms should be examined as a way of assessing ocean acidification in ocean surface waters in conjunction with *in situ* measurements (e.g., LIDAR to detect structural changes in coral reefs).

Attempts should be made to initiate measuring programs that are designed to discern impacts of acidification on calcifying and other marine organisms. Ocean acidification may lead to decreases in size-normalised (1) foraminifera and pteropod shell weight and thickness, (2) average PIC per coccolith, (3) proportions of malformed coccoliths and shells, (4) volumetric calcification rates (rate of uptake of radio-labeled carbon into $CaCO_3$), (5) abundances of calcifying organisms, and (6) average PIC concentration in open-ocean waters. Biological parameters such as these should be measured at time-series sites and on repeat surveys to allow detection of changes over time. After several decades, large-scale inhibition of calcification would also lead to a measurable increase in surface seawater alkalinity. Therefore, repeat surveys that include alkalinity as a measured variable should be encouraged, particularly into areas having high calcification rates, such as the low-latitude Pacific Ocean. Also, archiving of present-day organisms collected on cruises may prove useful for later comparisons.

Data Management

Data management and dissemination must be a part of the ocean acidification research that is planned from the beginning. Data must be reported and archived such that they are readily accessible now and in future decades. Likewise, data mining and archival of historical data may provide useful insights into the evolution of ocean acidification over time. This effort needs to be approached carefully, as there are many historical data that are not of sufficient quality to address these issues. A quality assessment effort should be conducted in conjunction with each data mining effort in order to confirm that data are useful.

Education and Outreach

Workshop participants recognized the necessity for interdisciplinary training of graduate students, post-doctoral investigators, and principal investigators to enhance observation networks, both regionally and globally. Suggestions included holding multi-disciplinary summer schools for experimentalists and modelers, involving national and international scientists. Initiatives for public outreach and education were also recommended. Meetings with coral-reef managers, fisheries managers and other stakeholders should be held to engage specific communities to develop ideas for monitoring strategies. Participants recommended tapping into existing programs to advance public education at the national and international level. Readily accessible presentations and fact sheets on ocean acidification and its effects on marine life should be created for the public and schools. Additional information should be made available via Web sites.

Discussion Group 3: Scaling organisms to ecosystem acidification effects and feedbacks on climate

Chair: Hans-Otto Pörtner (Alfred-Wegener Institute, Germany)
Rapporteur: Ken Caldeira (Carnegie Institute, USA)

Group 3 was asked to consider the following questions:

a. How can effects occurring on single organisms and small experimental populations be scaled up to ecosystem effects over time?
b. Can genetic changes be detected over experimental or observational periods and, if so, how can genetic changes occurring over these periods be extrapolated in order to evaluate potential effects over longer periods of time?
c. How can known changes in populations of organisms that are expected to be affected by ocean acidification (due currently to forcing from other than ocean acidification) be used to predict the potential future effects of ocean acidification?

Group 3 sub-divided the questions into 5 main topics and addressed the major research questions and key approaches as well as the methods and tools for addressing them.

Scaling up from organisms to ecosystems

A set of major research questions was identified to understand how we can scale up from single organisms to ecosystems:

1. Which ecosystems are at the greatest risk from ocean acidification and which of these are most important?
2. Are there clear ecological tipping points that can be defined in terms of pH or carbonate ion concentration?
3. What is the impact of ocean acidification on marine biodiversity?
4. What are impacts of ocean acidification on fisheries, food production, and other human uses or benefits [ecosystem services]?
5. What physiological processes are most important to the scaling issue?
6. What are the impacts of ocean acidification on population levels (consider typical population properties)?
7. How are impacts of ocean acidification on different life stages of individuals reflected at the ecosystem level?
8. How are organism responses and species interactions related?
9. What are the ecosystem-ecosystem linkages (e.g., how will changes in depth of remineralization affect ecosystems below the zone of remineralization) ?
10. What is the potential for migration and avoidance behavior to adjust to pH and carbonate ion changes?

<u>Research Approaches:</u>

Scaling up from black-box experimental results on individuals and populations to the ecosystem level requires mechanistic understanding of the physiology and genetics of organisms and how these interact to affect energy flows and ecosystem structures. Several different research and analysis approaches could be used to understand scaling better, including laboratory experiments, mesocosm studies, observations of ocean ecosystems, and ecosystem perturbation experiments. It may be possible to examine analogues from other kinds of environmental disturbance (e.g., overfishing can lead to explosion of sea urchins) to understand food-web effects.

First, it will be helpful to produce a matrix of key physiological processes related to calcification, acid-base control, and other processes affected by changes in pH and carbonate ion concentrations; identify sensitive organisms; and evaluate the role of these organisms in various ecosystems. Some long-term studies show impacts of various factors on ecosystems.

Using these sensitive organisms, laboratory experiments should focus initially on sensitivity indicators such as mortality, stress, and changes in performance to try to understand the mechanistic basis for sensitivity. Experimental conditions should include high- to low-level exposures, short- to long-term exposures, and various stages in the life history of sensitive organisms. Multiple natural populations (in addition to standardized laboratory strains) should be used in such experiments.

The genetics of the effects of changes in pH and carbonate ion concentrations are relatively unknown. It will be necessary to evaluate the plasticity in responses to changes in pH and carbonate ion concentrations, genetic diversity, and the relationship of genetics to sensitivity at population level. Physiological processes will need to be related to gene regulation, diversity, etc. (environmental genomics).

Ultimately, it will be important to model individual species to understand ecosystem-scale adaptation in terms of nutrient cycling, energy transfer through trophic levels, fecundity, etc.

Ocean acidification versus other ongoing changes in the marine environment

Because ocean acidification occurs simultaneously with other changes in the global ocean, Group 3 identified major research questions and associated uncertainties:

1. How do we isolate ocean acidification impacts from other causes of change in the observational context?
2. How do changes in temperature, salinity, light, nutrients, oxygen levels, human behavior (overfishing, pollution) etc, interact with ocean acidification? This includes
    a. Changes in weather and its variability.
    b. Changes in ocean circulation, large-scale cycles
    c. Changes in seasonal patterns, El Niño, etc.
3. Does ocean acidification make sensitive organisms more susceptible to disease?
4. How does ocean acidification affect the success of invasive species?
5. What are the relevant regimes of changes in temperature, pH, etc. that should be used by experimentalists interested in "realistic" scenarios?

Research Approaches:

Developing good observing systems in key areas will be fundamental for understanding how ocean acidification and other global changes interact. These systems should include measurements of ocean carbon system parameters as well as temperature, salinity, winds, nutrients, etc. In addition to good observations, it will be necessary to improve our understanding of the background state of sensitive organisms, including their physiological state (health, reproduction), as well as their burden of parasites and other disease. Multi-factorial experiments, both in the laboratory and in mesocosms, should be conducted. These experiments should rely on standardized protocols while including effective data management, sharing, and archiving. With results from these activities, modeling can be integrated with experiments to provide better understanding of how the systems work, as well as potentially developing predictive capabilities. Modelling efforts can also benefit by integrating results from the research activities related to the scaling up issue.

Scaling in time: adaptation and evolution

Major research questions related to understanding how sensitive organisms may adapt and evolve over time include the following:

1. To what extent will organisms be able to adapt (or evolve) to deal with ocean acidification?
    a. How fast can this adaptation or evolution occur and how does this compare with anticipated rates of change?
2. To what extent does gene flow and dispersal [life history, generation time] influence adaptability to ocean acidification?
3. Is there evidence of ongoing adaptation or evolution?
    a. What are the key gene regulatory networks for processes relating to ocean acidification?
    b. Are these gene abundances changing in the field?
4. How can changes from ocean acidification be distinguished from the effects of other global changes?
5. What are the relative roles of plasticity, acclimatization, and evolutionary adaptation?

    a. What are differences among closely related populations living in different environmental conditions?
    b. What are the relationships among generation time, plasticity, and adaptation?
6. How will the evolutionary adaptation of species affect species interaction?
7. What are time scales for ecosystem change and recovery?

<u>Research Approaches</u>:

The first approach would be to compare individuals and populations of the same species living in different areas with different natural pH values, for example, observing natural analogues such as CO_2 vents, understanding that this approach has some limitations. After they are identified, key genes should be monitored in natural populations to determine whether they are changing. An examination and analysis of the paleo-record may provide insights. Long-term laboratory and mesocosm experiments will be needed to study changes at the genetic level over the long term under environmentally relevant conditions (seasonal cycles, nutrient conditions, variability, etc.), including experiments that slowly ramp up CO_2 concentration to more closely mimic progressive change. Commitment to long-term studies is essential, which is difficult with 2-3 year funding cycles. Finally, selective breeding experiments can help provide information about the adaptability of organisms to changing pH and carbonate ion concentrations.

Feedbacks on climate and the carbon cycle

Major research questions that should be addressed to understand how ocean acidification could feed back on climate and the carbon cycle include the following:

1. How will ocean acidification affect production of dimethylsulfide (DMS) and other climatically important gases (and therefore climate)?
    a. How will the effects of ocean acidification on gas production interact with climate change?
    b. Are there other important radiative effects of ocean acidification (e.g., ocean albedo)?
2. How will the impact of ocean acidification on the microbial loop affect climatically important fluxes (DMS, other trace gases, carbon export)?
    a. How will the effects of ocean acidification on the microbial loop interact with climate change?
3. What are the long-term climate consequences of effects of ocean acidification on biogeochemical cycles?
    a. How will increased CO_2 content affect sediment dissolution?
    b. Will the effect of CO_2 fertilization significantly impact biogeochemical fluxes?
4. How will ocean acidification affect production of trace gases (e.g., halogen containing gases) that affect the ozone levels?
5. What are time scales for geochemical recovery?

<u>Research Approaches:</u>

The approaches to study how ocean acidification feeds back on climate and the carbon cycle include modeling, large-scale open-ocean perturbation experiments with CO_2 or a mineral acid, for which both legal and logistical concerns remain, and observation of natural analogues (e.g., upwelling systems).

Other questions to consider include the following:

1. Would intentional or unintentional perturbations to the sulfur cycle affect response to ocean acidification?
2. What is the relationship between proposed carbon sequestration approaches and ocean acidification?
    a. Ocean fertilization
    b. Direct injection
    c. Accelerated carbonate weathering
3. To what extent and at what scale are direct mitigation approaches possible?

5. Ocean in a High-CO_2 World Symposia

The first symposium on *The Ocean in a High-CO_2 World* (2004) proved to be a landmark event, even though it brought together only about half the number of scientists as attended the second symposium in Monaco. In 2004, the term "ocean acidification" was not in wide use, and only a small group of specialists had been studying how increasing marine concentrations of CO_2 and corresponding reductions in pH and carbonate ion concentrations were affecting marine organisms, mostly corals. At that time, ocean scientists were primarily studying the beneficial effects of the ocean's great capacity to take up CO_2, thereby moderating the increase in atmospheric CO_2 from fossil-fuel burning. But as the meeting progressed, there was a growing awareness of problems associated with corresponding changes in ocean chemistry and potential impacts on marine organisms.

The first symposium marked a turning point for many scientists, who suddenly understood that the impacts of ocean uptake of CO_2 were as important as assessing the air-sea CO_2 flux. The media also picked up on these growing concerns and interest increased rapidly as papers from the symposium were published in high-profile science journals (Feely et al., 2004; Sabine et al., 2004; Orr et al., 2005) and as scientific reviews were released by the UK Royal Society (Raven et al., 2005), by OSPAR Commission (Haugan et al., 2006), by NSF, NOAA, and the U.S. Geological Survey (Kleypas et al., 2006), and by the German Advisory Council (Schubert et al., 2006).

Four years later, under heightened concern, the scientific community was reunited for a second symposium on *The Ocean in a High-CO_2 World*. The interest in ocean acidification has grown, as demonstrated by the 220 scientists from 32 countries that came to Monaco to participate during October 6-9, 2008. During just the 4 years that elapsed between the two symposia (2005-2008), there have been 168 scientific papers on the topic of ocean acidification, whereas during the preceding 55 years (1949-2004) there were 158 papers (Gattuso, 2008b). Ocean acidification is now widely cited in the press in conjunction with climate change, often being referred to as "the other CO_2 problem". Highlights of some of the recent results that were presented at the second symposium include

- New studies focusing on the polar oceans and when their surface waters will start to become undersaturated with respect to aragonite, leading some scientists to suggest stabilizing atmospheric CO_2 at no more than 450 ppmv to limit these severe conditions;
- New studies indicating that shell weights of Southern Ocean foraminifera and pteropods are decreasing, which may be due to ocean acidification;
- New perturbation experiments showing that the rate of calcification of an Arctic pteropod declines at lower pH
- A new study demonstrating that cold-water coral calcification decreases under high-CO_2 conditions;

- A new study of the impact of increased ocean CO_2 and temperature on larval stages of oysters revealing negative effects from ocean acidification, but also that these effects are much less severe in oysters that have been bred selectively to be more resilient to disease;
- New perturbation experiments revealing deleterious effects of ocean acidification on invertebrate reproduction and larval stages;
- New studies showing how ecosystems react to naturally high-CO_2 conditions near seafloor vents, where ecosystem changes generally follow expected trends based on previous understanding gained from laboratory perturbation experiments; and
- New studies revealing that ocean acidification is affecting sound propagation and noise in the ocean.

Scientists at the 2008 symposium identified new research priorities, based on needs for further investigation and current limitations for observations, methods, and technology (Section 4). Participants stressed the importance of improving international coordination to facilitate agreements on protocols, methods, and data reporting and to optimize our limited resources by greater sharing of materials, facilities, expertise, and data.

Symposium participants recognized the importance of developing strong links with end-users of ocean acidification research results, in order to guide information and product development and to better disseminate this information to appropriate audiences. Despite major uncertainties, the research community must prioritize finding ways to scale-up understanding of biological responses of individual organisms to provide meaningful predictions of how ocean acidification will affect food webs, fisheries, and tourism. Researchers will also need to develop easy-to-understand information that would be particularly useful to end-users, such as simple indicators of change and thresholds beyond which the ecosystem will not recover.

Increasing atmospheric CO_2 concentrations drive both ocean acidification and climate change, but they are separate issues involving different research communities. Scientists emphasized that there must be a greater effort to integrate results from ocean acidification research, which is still in its infancy, into the IPCC process and post-Kyoto negotiations that are aimed at reducing CO_2 emissions.

The third symposium on the *Ocean in a High-CO_2 World*, planned for 2012, will assess advances made since the second symposium.

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