The Ocean in a High-CO_2 World

BY THE SCOR/IOC SYMPOSIUM PLANNING COMMITTEE

INTRODUCTION

The present atmospheric concentration of carbon dioxide has not been exceeded during the past 420,000 years, and possibly not during the past 15 million years. The present sustained rate of increase is unprecedented, at least during the past 20,000 years (Prentice et al., 2001). This rise is expected to continue, leading to significant global temperature increases by the end of this century. It is very likely that the partial pressure of CO_2 (pCO_2) in the surface ocean will double over its pre-industrial value by the middle of this century. Accompanying surface ocean pH changes three times greater than those experienced during the transition from glacial to interglacial periods are predicted, which could have profound impacts on marine organisms and ecosystems.

The ocean, one of the largest natural reservoirs of carbon, is buffering the changes in atmospheric CO_2. The ocean has absorbed about one-third of the CO_2 released from all human activities (emissions from fossil fuels, cement manufacturing, and land-use changes) from 1800 to 1994 (Sabine et al., 2004). Over the next few millennia, the ocean is predicted to absorb approximately 90 percent of the CO_2 emitted to the atmosphere, after atmospheric CO_2 concentrations are stabilized. In the geologic past, the ocean has experienced periods of large fluctuations in ocean chemistry and circulation that undoubtedly led to alterations in ocean ecosystems, but the concern today is that the current rate of warming and acidification is probably much faster than experienced in the past, perhaps too fast for ecosystems to adapt to the changes.

Changes in the ocean's pH are already affecting the calcium carbonate system in the ocean (Feely et al., 2004), which is shown by expansion of areas of undersaturation of calcite and aragonite in the global ocean. Such undersaturation will potentially have a serious impact on marine organisms.

Owing to sustained measurements of oceanic CO_2 that now span more than one decade in some locations, we can begin to document the trend of increasing dissolved inorganic carbon (DIC) concentrations that follow the rise in the atmospheric CO_2 concentration (Figure 1).

The pH reduction, which is already measurable, is expected to become more pronounced as atmospheric CO_2 concentrations continue to rise (Figure 2). Figure 2 shows the range of present-day surface water pH values at current atmospheric CO_2 concentrations. The figure also indicates estimated pH during pre-industrial (glacial and interglacial) times. If atmospheric CO_2 reaches 750 ppm, probably around year 2100, pH will be 0.3 units lower than today's values.

As scientists and decision-makers look for ways to resolve the current crisis of increasing CO_2 and its impending impacts on climate, one option being examined to help stabilize atmospheric CO_2 concentrations is to store excess CO_2 in plant biomass, geological reservoirs, or the deep ocean. The potential strategies for sequestering atmospheric CO_2 in the ocean 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 injecting it directly into the deep ocean. Although relevant research has been conducted in the past decade, the potential effectiveness and risks of these forms of carbon

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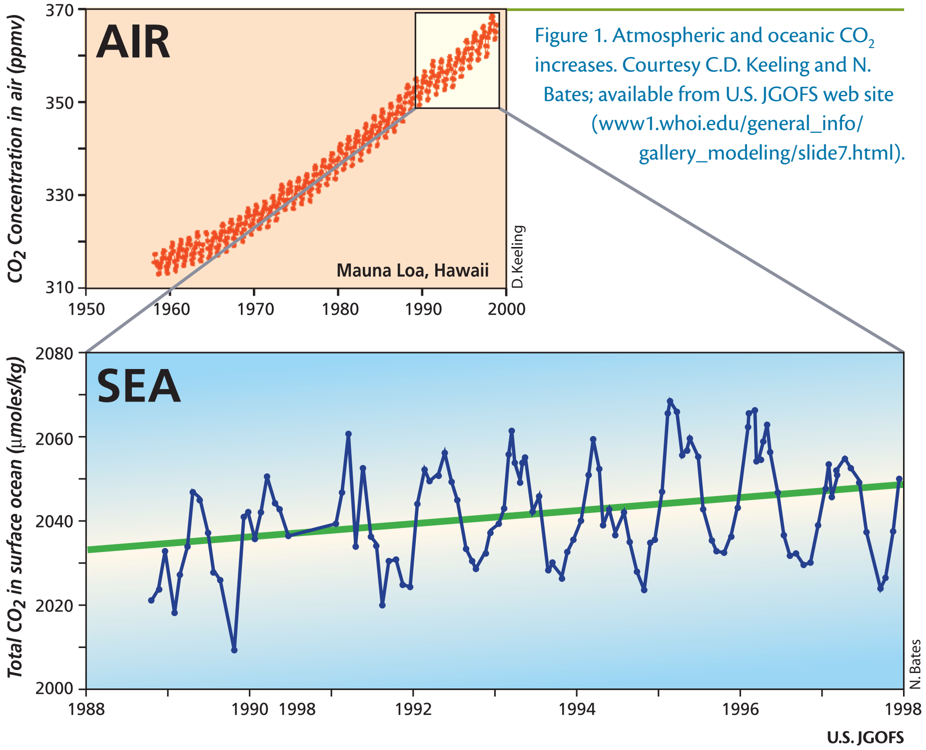

Figure 1. Atmospheric and oceanic CO_2 increases. Courtesy C.D. Keeling and N. Bates; available from U.S. JGOFS web site (www1.whoi.edu/general_info/gallery_modeling/slide7.html).

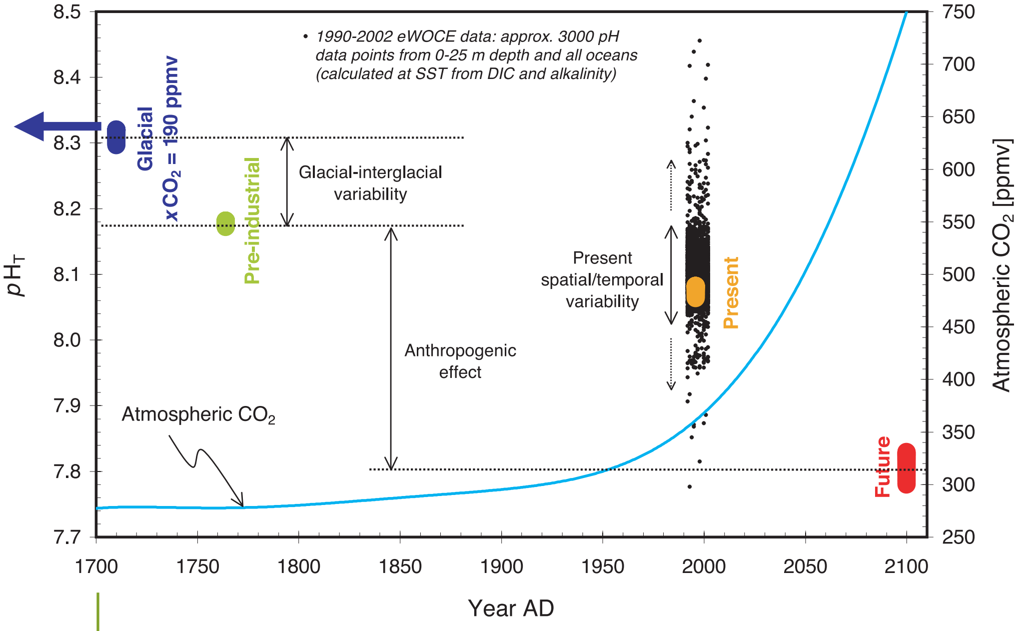

Figure 2. Present (1990-2002) surface seawater pH_T values from all oceans (3000 data points from the upper 25 m, pH_T were calculated from measured dissolved inorganic carbon and alkalinity). The majority of the data fall into a rather narrow pH range of 8.1 ± 0.1. Also shown are typical pH ranges of glacial, pre-industrial, present, and future (year 2100) surface seawaters resulting from the observed and predicted increase in atmospheric CO_2 levels (blue line with exponential increase) as obtained by simple scenario calculation. Figure prepared by Arne Körtzinger on the basis of WOCE data (Schlitzer, 2000). From IMBER (In prep.).

sequestration in the ocean have not been thoroughly discussed and assessed.

Potential biological impacts of both passive invasion of anthropogenic CO_2 into the surface ocean and active sequestration of carbon in the ocean are only poorly known. 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, as well as accurate parameter values for monitoring and quantifying changes from the present ocean.

To address the biological and biogeochemical consequences of increasing atmospheric and oceanic CO_2 levels, and possible strategies for mitigating such increases, 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.[1, 2] Topics ranged from ocean physics to chemistry and biology, including the impacts of elevated CO_2 levels on marine life, the dissolution of calcium carbonate, and 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 CO_2 in the ocean, but did identify what scientific information is available, and what is still needed, to make informed policy decisions.

SYMPOSIUM DISCUSSION GROUPS AND OUTCOMES

Symposium participants divided into three groups to discuss biological and chemical consequences to the ocean of a high-CO_2 world, and recommendations for future research to study these consequences.

High-CO_2 Group

In a high-CO_2 world, increased atmospheric pCO_2 will increase surface ocean (and eventually deep ocean) pCO_2 and lower its pH. These changes in pCO_2 and pH will accompany changes to other environmental variables. For example, it is likely that increased pCO_2 will be accompanied by increased surface ocean 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 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, as well as the combined effects of higher pCO_2 levels, higher temperature, and lower O_2 concentrations. A research priority will be to predict future changes in ocean carbonate chemistry, and how these changes will affect calcitic and aragonitic organisms.

Increased oceanic pCO_2 and associated environmental changes are expected to affect calcifying organisms, but their effects on non-calcifying organisms also need to be studied. Combined effects of two or more variables (e.g., pCO_2 and temperature) may be particularly important. Specifically, research should include the effects of increased atmospheric pCO_2 on

- Community structure and composition (including how species-specific responses will affect community composition), from bacteria to vertebrates.
- Genetic diversity, species diversity, and the diversity of functional groups.
- 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. Although extant organisms were able to evolve quickly enough to adapt to past global changes, will they be able to adapt to the more rapid pace of current change? Can adaptation occur under a continually and rapidly changing environment versus one that eventually stabilizes?
- Sub-lethal effects, including organismal reproductive potential, growth, and susceptibility to disease.

Increasing surface ocean pCO_2 and de-

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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. 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] See also Cicerone et al. (2004).

creasing 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? Because 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 dependence). 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?
- Dissolved Organic Matter (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 matter 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?

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. Priority areas for study are the following:

- 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.”
- Ecosystems in the intertidal and shallow subtidal areas.
- Ecosystems in the mesopelagic zone.
- Ecosystems in the Southern Ocean and subarctic Pacific Ocean.
- Productive ecosystems that provide living marine resources, such as fish.

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[3] 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 CO_2 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 ecosystems. These experiments involve adding CO_2 to the air sur-

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[3] Mesocosms are enclosed parcels of seawater (the Bergen National Mesocosm Centre’s mesocosms contain volumes between 2 and 30 m^3) in a semi-natural environment. The mesocosms are either on land or suspended in the ocean. Typical mesocosm experiments last for 3 to 6 weeks and are usually carried out by interdisciplinary teams. They are used to study species composition and ecosystem changes that occur when physical, chemical and biological parameters are manipulated. The same conditions are typically replicated in several enclosures to quantify variability within each particular treatment.

rounding vegetated land areas continuously for several years to maintain elevated atmospheric CO_2 levels that mimic those likely to be experienced in the next 50 years. These experiments involve encircling plots of land with controlled diffusers for CO_2, and bathing the vegetation (trees, grasses, and crops) in elevated atmospheric CO_2 levels to simulate the anticipated conditions of the later 21st Century. These experiments have demonstrated how plant communities will respond to elevated atmospheric CO_2 on both seasonal and interannual bases. 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. FACE-like experiments have been proposed in the ocean. The benefit of such experiments is that they are more likely to show actual future long-term effects. The major anticipated drawback is that it might be impossible to do this type of experiment 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[4] required for a full-scale pelagic FACE experiment may be very large. The other potential drawback is negative public perception. To overcome negative perceptions of such experiments, the case will need to be made that it is better to make informed decisions based on knowledge of the likely magnitude of the effects of elevated CO_2 and decreased pH in ocean waters than to assume that global CO_2 emissions can continue (or ocean carbon sequestration can be initiated) without negative effects on marine ecosystems.

- ***Model development.*** Ongoing development of models to assess the role of climate feedback and elevated CO_2 levels on ocean ecosystems and biogeochemistry should be pursued. 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 among functional biodiversity, ecosystem functioning, and the fluxes of elements and associated feedbacks are no longer appropriate.
- ***Other approaches.*** Other important research and observational 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 those 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.

Mitigation Group

The second group discussed research priorities related to the efficiency of carbon 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 are necessary before informed decisions can be made about whether ocean carbon sequestration is technically feasible. Field experiments, modeling experiments, or both are required. An important idea discussed was that ocean carbon sequestration techniques may be suitable in some places and times as "niche applications," for example, to sequester industrial CO_2 produced in coastal areas adjacent to the deep ocean.

- ***CO_2 Injection.*** What is the long-term storage efficiency of injected CO_2? How much does the efficiency depend on where (location and depth), when, and how the injection is done? Field experiments will probably require that tracers such as SF_6 are injected with the carbon to elucidate the mixing and advection mechanisms that might move the CO_2 patch; global circulation models and finer-scale models may not now include all appropriate mechanisms. Other specific questions include
  - How will elevated carbon concentrations spread over time and space?
  - Under what conditions does the

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[4] 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.

benthic boundary layer homogenize at sufficiently low carbon concentrations so that further diffusion is reduced to a passive tracer problem?
    - Under what conditions does the benthic boundary layer mix with ambient water sufficiently to eliminate strong concentration gradients in CO_2, and what are the time scales for these mixing processes?
    - How do $CaCO_3$-rich sediments respond to elevated carbon concentration?
    - On the microscale, how do CO_2 hydrates form and dissolve?
- ***Iron Fertilization.*** 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, however, that iron fertilization would be a very inefficient method of ocean carbon sequestration. The amount of carbon that could be sequestered by this method is relatively small and even if the iron requirements of phytoplankton were met, other nutrients and environmental factors would become limiting (Boyd, 2004). Modeling studies, such as initiated by Gnanadesikan et al. (2003), should continue to assess likely effectiveness of iron fertilization on the drawdown of atmospheric CO_2 using information gained from continuing field studies.

Impacts of Sequestration

- ***CO_2 Injection.*** Far-field effects on marine life of CO_2 injected into the deep ocean need to be studied and modeled because the injected CO_2 will disperse and be advected throughout the ocean on the time scale of ocean circulation, which is roughly 500 years. Long-term studies could be conducted in locations of restricted advection, such as fjords. Regions where the anthropogenic signal is already penetrating into the deep sea, such as in some parts of the North Atlantic Ocean, should also be studied since the pH is already changing there. What are the mechanisms by which CO_2 causes sub-lethal effects or kills organisms? Studies of the effects of high CO_2 levels on deep-sea animals should be conducted under high pressures, at low temperatures, and with varying levels of CO_2.
- ***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 remineralized by bacteria, bacterial respiration will use oxygen. Most models have assumed complete utilization of existing nutrient inventories, and 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 and ecosystems. In addition to assessing the effectiveness of iron fertilization as a carbon sequestration technique, it is essential to assess the cumulative effects of iron fertilization on production of climate-reactive gases such as N_2O (a greenhouse gas), and DMS (dimethylsulfide, which affects marine aerosol production, a climate-feedback mechanism).

Approaches

This discussion group also recommended CO_2 perturbation experiments in the deep sea, where CO_2 would be injected. 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 Marianas Trench, and many submarine-vent and mud-volcano regions). 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 research area 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

An important outcome of the symposium was the realization that the impact on the ocean of increasing atmospheric CO_2 has not been adequately conveyed to the general scientific community and the public. Therefore, one discussion group formulated a plan to communicate this important scientific information more widely. This group agreed that the message 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 ocean's 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 indicates that increasing oceanic CO_2 and decreasing pH will have a profound effect on corals, shellfish, and specific groups of phytoplankton, but possibly also on non-calcifying organisms. 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 policy-makers 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 carbon sequestration approaches that do not involve the ocean.

Audience

The scientific community should be the first audience to receive the message about rising CO_2 levels and associated acidification of the ocean. Many ocean scientists attending the symposium were not aware of the seriousness of the issue. Policy-makers and regulators should be the next audience for this message because they need information about the adverse effects of elevated CO_2 levels to be able to make good policy decisions. The general public is the third group that needs to be informed of the consequences of increased atmospheric CO_2 levels, in addition to CO_2's contribution to global warming. Finally, this message should be conveyed to college and high-school students because their generation will suffer the consequences of today's government policies for CO_2 control.

Mechanisms

The message about ocean acidification should be conveyed through a variety of mechanisms, to reach the different audiences, including a special section of papers from the symposium in the *Journal of Geophysical Research—Oceans,* summary articles in various places, an updated meeting web site (including relevant images), and continued attention to the topic by SCOR and IOC.

SUMMARY AND CONCLUSIONS

Increases in atmospheric CO_2 from human activities are a serious problem because CO_2 is a greenhouse gas known to absorb infrared radiation and increase the temperature of the lower atmosphere. The ocean is estimated to have absorbed about one-third of the CO_2 released from human activities from 1800 to 1994, probably reducing temperature increases. However, this mitigation of atmospheric CO_2 increases has been achieved at a price to the ocean of decreased pH. Continuing increases in release of CO_2 to the atmosphere or purposeful sequestration of CO_2 in the ocean will result in consequences that are unpredictable. Research on the potential effects of generalized pH changes (from passive absorption of CO_2 by the surface ocean) and localized pH change from deep-ocean injection should be conducted to help policy-makers know the potential impacts of allowing atmospheric CO_2 concentrations to increase, as well as the impacts of deep-ocean injection. Fertilization of the surface ocean with iron or other nutrients appears to be inefficient and to present many potential drawbacks. Scientists, policy-makers, and the public should be made aware of the issue of ocean acidification.

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