Introduction to special section: The Ocean in a High-CO_2 World

James C. Orr

Laboratoire des Sciences du Climat et de l'Environnement, Commissariat à l'Energie Atomique/Centre National de la Recherche Scientifique, Gif-sur-Yvette, France

Silvio Pantoja

Departamento de Oceanografía and Center for Oceanographic Research in the Eastern South Pacific/Fund for Advanced Research in Priority Areas, Universidad de Concepción, Concepción, Chile

Hans-Otto Pörtner

Marine Biology/Ecological and Evolutionary Physiology, Alfred-Wegener-Institute, Bremerhaven, Germany

Received 3 June 2005; revised 16 June 2005; accepted 29 June 2005; published 17 September 2005.

Citation: Orr, J. C., S. Pantoja, and H.-O. Pörtner (2005), Introduction to special section: The Ocean in a High-CO_2 World, *J. Geophys. Res.*, *110*, C09S01, doi:10.1029/2005JC003086.

[1] The ocean's vast capacity to take up anthropogenic CO_2 helps limit increases in atmospheric CO_2, thus moderating climate. Unfortunately, this passive uptake also implies a reduction in surface ocean pH. Such ocean acidification occurs because CO_2 reacts with water, increasing hydrogen ions; simultaneously, bicarbonate ions increase and carbonate ions decrease. Because passive ocean uptake cannot keep pace with increases of atmospheric CO_2, there have been proposals to actively enhance ocean uptake of CO_2. Both passive and active uptake of anthropogenic CO_2 will also affect ocean biology via changes in ocean chemistry.

[2] To help assess and promote research into the consequences of ocean acidification, the Scientific Committee on Oceanic Research (SCOR) and the Intergovernmental Oceanographic Commission of UNESCO (IOC) jointly organized the scientific symposium "The Ocean in a High CO_2 World" at UNESCO in Paris in May 2004. About 125 scientists met to discuss future changes in ocean carbonate chemistry and biology due to both passive and active ocean uptake of anthropogenic CO_2 [*Cicerone et al.*, 2004a, 2004b]. Shortly thereafter, two papers that were presented at that symposium appeared [*Feely et al.*, 2004; *Sabine et al.*, 2004]. These events led to a flood of related articles in the popular press (see http://ioc.unesco.org/iocweb/CO2panel/SymposiumMedia.htm).

[3] The following special section offers a collection of 16 additional scientific papers that stem from the same symposium. The focus remains on the drawbacks of the anthropogenic CO_2 invasion, namely the impacts of invading CO_2 on ocean chemistry and biology.

[4] The ocean's anthropogenic component of dissolved inorganic carbon (DIC) cannot be measured directly because of large natural background DIC concentrations. However, data-based quantification methods were developed a quarter of a century ago and have been substantially improved during the last decade. With three recent data-based methods, *Lo Monaco et al.* [2005] estimate anthropogenic CO_2 using data collected along the WOCE I6 section (along 30°E). South of 50°S, they find much larger inventories of anthropogenic CO_2 than estimated previously. This is the same region where ocean models simulate large but very different air-sea fluxes of anthropogenic CO_2. *Álvarez et al.* [2005] also use a data-based method to estimate storage and lateral transport of anthropogenic CO_2 in the Mediterranean Sea. Although numbers for the Mediterranean appear small in terms of global ocean uptake, the impact on local carbonate chemistry will be large and will affect dense population centers.

[5] To estimate future DIC concentrations and related changes in carbonate chemistry, we must rely on models. One global ocean model driven by a range of IPCC scenarios simulates that average surface pH will be reduced by 0.3–0.5 by 2100 [*Caldeira and Wickett*, 2005]. By 2300, the pH decline reaches 0.8 and 1.4 for two scenarios with fossil emissions of 5000 and 20,000 Pg C. The same study also reveals that there will be dramatic changes in carbonate ion concentrations and aragonite and calcite saturation states. Another model study [*Archer*, 2005] points out the long-term nature of our unintentional, global-scale, fossil CO_2 perturbation experiment, which will be felt for about 100,000 years, thereby affecting methane clathrate deposits, ice sheets, and glacial-interglacial dynamics.

[6] Yet, even on much shorter timescales, changes in atmospheric CO_2 as well as changes in other environmental variables may severely impact ocean biota. *Hoegh-Guldberg* [2005] reviews evidence suggesting that corals could become rare by the middle of this century because of simultaneous increases in temperature and decreases in carbonate ion concentration. *Langdon and Atkinson* [2005] use manipulative experiments to quantify changes in coral calcification and net carbon production. They find a strong linear relationship of coral calcification to aragonite saturation state (Ω_A), with calcification becoming negative (dissolution) when $\Omega_A < 1$. Their results support the hypothesis that cellular calcification and photosynthesis compete for a limited supply of DIC.

[7] Although corals have received the most attention so far, they will not be the only marine organisms that will feel

0148-0227/05/2005JC003086$09.00

increases in atmospheric CO_2. *Shirayama and Thornton* [2005] found that even moderate increases in atmospheric CO_2 to 550 ppmv, a level which is likely to be reached by the middle of this century, will adversely affect other shallow water marine benthic organisms by reducing their growth, calcification, and survival. Sea urchins that form parts of their exoskeletons out of magnesium calcite appear particularly threatened.

[8] *Ishimatsu et al.* [2005] review the acute and chronic effects of high aqueous CO_2 on fish physiology. These effects include reduced respiration, blood circulation, reproductive activity, and growth. They point to a collapse in circulation as the cause of acute mortality at high CO_2 levels, such as would be expected at local sites chosen for active deep ocean sequestration.

[9] *Pörtner et al.* [2005] provide an overview of short- and long-term effects of increasing CO_2 on various physiological mechanisms in marine animals. They show that chronic exposure in invertebrates first results in a general depression of physiological functions, including rates of metabolism, activity, and growth; subsequently, chronic exposure also leads to enhanced mortality. Effects from higher CO_2 will likely exacerbate those from increased temperatures and decreased dissolved O_2. Thus the thermal window of a given species may become narrower as will its geographical distribution.

[10] The passive uptake of anthropogenic CO_2 by the ocean will occur throughout the surface ocean and will gradually invade the deep ocean. On the other hand, if some of the CO_2 that would to be released to the atmosphere were instead actively sequestered in the deep ocean, changes in the surface ocean would be reduced at the expense of much larger local changes in the deep ocean [*Caldeira and Wickett*, 2005]. Before such a scenario could be implemented, we need to improve our understanding of the near-range effects on local chemistry and biology.

[11] *Nakayama et al.* [2005] evaluated possible fundamental physical chemistry impediments to carrying out future small-scale Free-Ocean CO_2 Enrichment (FOCE) experiments. These FOCE experiments would be analogous to the numerous terrestrial biosphere Free-Air CO_2 Enrichment (FACE) experiments already underway, which provide a high-CO_2 controlled ambient environment designed for conducting manipulative studies. However, it has been thought that the ocean CO_2 system might equilibrate more slowly at depth, thereby complicating FOCE studies. Yet *Nakayama et al.* [2005] find just the opposite: the CO_2 system equilibrates more rapidly at 1000 m, with waters at 4°C, than it does at the surface. This finding appears to clear the way for future FOCE studies.

[12] The same kinds of perturbation experiments that were used to study ocean chemistry were also conducted with the idea to determine the effects of small-scale injections of liquid CO_2 on deep sea meiofauna [*Barry et al.*, 2005]. These organisms, which normally live in relatively stable environments, exhibited low but variable survival rates when they were subjected to periodic, short-lived pH perturbations of up to 0.2.

[13] In contrast to such artificial injection experiments, a natural opportunity to study the effect of high CO_2 on deep sea fauna is provided by high-CO_2 plumes emanating from hydrothermal vents on the Loihi Seamount near Hawaii. With baited traps exposed to these high-CO_2 plumes, *Vetter and Smith* [2005] show that caged amphipods became narcotized when they were exposed to diluted vent waters with a mean pH of 6.3. Yet when open bait bundles were placed in similar CO_2 plumes they were avoided by amphipods, synaphobranchid eels, and hexanchid sharks, suggesting that these scavengers are able to detect such unfavorable conditions. In contrast, vent specialist shrimp were attracted by the bait and appeared unaffected by the elevated CO_2 concentrations.

[14] These experiments with deep ocean, benthic fauna might be most pertinent for the proposed active CO_2 sequestration scenario where liquid CO_2 is delivered to a topographic low on the deep ocean floor (liquid CO_2 lake scenario). *Haugan and Alendal* [2005] model this scenario and suggest that the stability of such a lake may well be susceptible to local gravity currents.

[15] Local impacts on the benthos could be reduced if instead liquid CO_2 were injected into the middle of the water column. *Chen et al.* [2005] model injected liquid CO_2 plume dynamics and corresponding local changes in ocean physics and chemistry. They show that local pH changes can be reduced dramatically with judicious choices for the delivery scheme, injection rate, droplet size, and bottom bathymetry.

[16] *De Baar et al.* [2005] synthesize results of 8 in situ artificial iron fertilization experiments carried out during 1993 to 2002 in the Equatorial Pacific, the Southern Ocean, and the subarctic Pacific. They find that the depth of the wind-mixed layer defines the maximum chlorophyll a, the maximum DIC removal, and the overall DIC/Fe efficiency ($\sim$5600 for DIC uptake during all experiments). These experiments have substantially advanced our knowledge about the iron cycle in the ocean and are fundamental to developing realistic ocean biogeochemistry and ecosystem models. For instance, *Legendre and Rivkin* [2005] propose a conceptual approach for modeling upper ocean functional biodiversity, food web processes, and biogeochemical carbon fluxes, and they use it to make preliminary predictions concerning possible future iron fertilization. Other modeling studies discussed at the symposium emphasize that iron fertilization would provide an inefficient means to actively sequester CO_2 in the future. Furthermore, using iron fertilization as a mitigation strategy would probably have serious side effects (e.g., decreased dissolved O_2, increased atmospheric N_2O, and decreased nutrients downstream from a fertilization site).

[17] The papers in this special section of *Journal of Geophysical Research–Oceans* will contribute, along with other publications and research that extend from the same symposium, to an improved understanding of how ocean biogeochemistry and ecosystems will operate in the future, high-CO_2 world. Currently, SCOR and UNESCO-IOC are discussing the possibility of co-organizing a similar symposium on a regular basis to contribute to the IPCC process.

[18] **Acknowledgments.** We thank Maria Hood (UNESCO-IOC) and Ed Urban (SCOR) for spearheading the organization of the symposium of "The Ocean in a High-CO_2 World" as well as for their continued diligence in promoting related research activities. The symposium organization and travel support came from the U.S. National Science Foundation Ocean Sciences Division (grants 0003700 and 0326301), the Research Council of Norway, and the Intergovernmental Oceanographic Commission of

UNESCO. Further information may be obtained at http://ioc.unesco.org/iocweb/CO2panel/HighOceanCO2.htm.

References

Álvarez, M., F. F. Pérez, D. R. Shoosmith, and H. L. Bryden (2005), Unaccounted role of Mediterranean Water in the drawdown of anthropogenic carbon, *J. Geophys. Res.*, *110*, C09S03, doi:10.1029/2004JC002633.

Archer, D. (2005), Fate of fossil fuel CO_2 in geologic time, *J. Geophys. Res.*, doi:10.1029/2004JC002625, in press.

Barry, J. P., K. R. Buck, C. Lovera, L. Kuhnz, and P. J. Whaling (2005), Utility of deep sea CO_2 release experiments in understanding the biology of a high-CO_2 ocean: Effects of hypercapnia on deep sea meiofauna, *J. Geophys. Res.*, *110*, C09S12, doi:10.1029/2004JC002629.

Caldeira, K., and M. E. Wickett (2005), Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean, *J. Geophys. Res.*, doi:10.1029/2004JC002671, in press.

Chen, B., Y. Song, M. Nishio, S. Someya, and M. Akai (2005), Modeling near-field dispersion from direct injection of carbon dioxide into the ocean, *J. Geophys. Res.*, doi:10.1029/2004JC002567, in press.

Cicerone, R., J. C. Orr, P. Brewer, P. Haugan, L. Merlivat, T. Ohsumi, S. Pantoja, and H.-O. Poertner (2004a), The ocean in a high CO_2 world, *Eos Trans. AGU*, *85*(37), 351–353.

Cicerone, R., J. C. Orr, P. Brewer, P. Haugan, L. Merlivat, T. Ohsumi, S. Pantoja, and H.-O. Poertner (2004b), The ocean in a high CO_2 world, *Oceanography*, *17*, 73–78.

De Baar, H., et al. (2005), Synthesis of iron fertilization experiments: From the Iron Age in the Age of Enlightenment, *J. Geophys. Res.*, doi:10.1029/2004JC002601, in press.

Feely, R. A., C. L. Sabine, K. Lee, W. Berelson, J. Kleypas, V. J. Fabry, and F. J. Millero (2004), The impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans, *Science*, *305*, 362–366.

Haugan, P. M., and G. Alendal (2005), Turbulent diffusion and transport from a CO_2 lake in the deep ocean, *J. Geophys. Res.*, doi:10.1029/2004JC002583, in press.

Hoegh-Guldberg, O. (2005), Low coral cover in a high-CO_2 world, *J. Geophys. Res.*, *110*, C09S06, doi:10.1029/2004JC002528.

Ishimatsu, A., M. Hayashi, K.-S. Lee, T. Kikkawa, and J. Kita (2005), Physiological effects on fishes in a high-CO_2 world, *J. Geophys. Res.*, *110*, C09S09, doi:10.1029/2004JC002564.

Langdon, C., and M. J. Atkinson (2005), Effect of elevated pCO_2 on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment, *J. Geophys. Res.*, *110*, C09S07, doi:10.1029/2004JC002576.

Legendre, L., and R. B. Rivkin (2005), Integrating functional diversity, food web processes, and biogeochemical carbon fluxes into a conceptual approach for modeling the upper ocean in a high-CO_2 world, *J. Geophys. Res.*, *110*, C09S17, doi:10.1029/2004JC002530.

Lo Monaco, C., C. Goyet, N. Metzl, A. Poisson, and F. Touratier (2005), Distribution and inventory of anthropogenic CO_2 in the Southern Ocean: Comparison of three data-based methods, *J. Geophys. Res.*, *110*, C09S02, doi:10.1029/2004JC002571.

Nakayama, N., E. T. Peltzer, P. Walz, and P. G. Brewer (2005), First results from a controlled deep sea CO_2 perturbation experiment: Evidence for rapid equilibration of the oceanic CO_2 system at depth, *J. Geophys. Res.*, *110*, C09S11, doi:10.1029/2004JC002597.

Pörtner, H. O., M. Langenbuch, and B. Michaelidis (2005), Synergistic effects of temperature extremes, hypoxia, and increases in CO_2 on marine animals: From Earth history to global change, *J. Geophys. Res.*, doi:10.1029/2004JC002561, in press.

Sabine, C. L., et al. (2004), The ocean sink for anthropogenic CO_2, *Science*, *305*, 367–370.

Shirayama, Y., and H. Thornton (2005), Effect of increased atmospheric CO_2 on shallow water marine benthos, *J. Geophys. Res.*, *110*, C09S08, doi:10.1029/2004JC002618.

Vetter, E. W., and C. R. Smith (2005), Insights into the ecological effects of deep ocean CO_2 enrichment: The impacts of natural CO_2 venting at Loihi seamount on deep sea scavengers, *J. Geophys. Res.*, *110*, C09S13, doi:10.1029/2004JC002617.

J. C. Orr, Laboratoire des Sciences du Climat et de l'Environnement, CEA Saclay, Bât. 709, L'Orme, F-91191 Gif-sur-Yvette, France. (orr@cea.fr)

S. Pantoja, Center for Oceanographic Research in the Eastern South Pacific/Fund for Advanced Research in Priority Areas, Universidad de Concepción, Casilla 160-C, Concepción, Chile. (spantoja@udec.cl)

H.-O. Pörtner, Marine Biology/Ecological and Evolutionary Physiology, Section: Animal Ecophysiology, Alfred-Wegener-Institute, Postfach 12 01 61, Columbusstrasse, D-27568 Bremerhaven, Germany. (hpoertner@awi-bremerhaven.de)