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Introduction to special section: The Ocean in a High-CO₂ World

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[1] The ocean's vast capacity to take up anthropogenic CO₂ helps limit increases in atmospheric CO₂, thus moderating climate. Unfortunately, this passive uptake also implies a reduction in surface ocean pH. Such ocean acidification occurs because CO₂ 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 CO₂, there have been proposals to actively enhance ocean uptake of CO₂. Both passive and active uptake of anthropogenic CO₂ 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 CO₂ 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 CO₂ [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 CO₂ invasion, namely the impacts of invading CO₂ 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 anthro-

pogenic CO₂ using data collected along the WOCE I6 section (along 30°E). South of 50°S, they find much larger inventories of anthropogenic CO₂ than estimated previously. This is the same region where ocean models simulate large but very different air-sea fluxes of anthropogenic CO₂. Alvarez *et al.* [2005] also use a data-based method to estimate storage and lateral transport of anthropogenic CO₂ 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 CO₂ 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 CO₂ 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

increases in atmospheric CO₂. *Shirayama and Thornton* [2005] found that even moderate increases in atmospheric CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ will likely exacerbate those from increased temperatures and decreased dissolved O₂. Thus the thermal window of a given species may become narrower as will its geographical distribution.

[10] The passive uptake of anthropogenic CO₂ by the ocean will occur throughout the surface ocean and will gradually invade the deep ocean. On the other hand, if some of the CO₂ that would 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 CO₂ Enrichment (FOCE) experiments. These FOCE experiments would be analogous to the numerous terrestrial biosphere Free-Air CO₂ Enrichment (FACE) experiments already underway, which provide a high-CO₂ controlled ambient environment designed for conducting manipulative studies. However, it has been thought that the ocean CO₂ system might equilibrate more slowly at depth, thereby complicating FOCE studies. Yet *Nakayama et al.* [2005] find just the opposite: the CO₂ 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 CO₂ 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 CO₂ on deep sea fauna is provided by high-CO₂ plumes emanating from hydrothermal vents on the Loihi Seamount near Hawaii.

With baited traps exposed to these high-CO₂ 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 CO₂ plumes they were avoided by amphipods, synbranchid 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 CO₂ concentrations.

[14] These experiments with deep ocean, benthic fauna might be most pertinent for the proposed active CO₂ sequestration scenario where liquid CO₂ is delivered to a topographic low on the deep ocean floor (liquid CO₂ 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 CO₂ were injected into the middle of the water column. *Chen et al.* [2005] model injected liquid CO₂ 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 (~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 CO₂ in the future. Furthermore, using iron fertilization as a mitigation strategy would probably have serious side effects (e.g., decreased dissolved O₂, increased atmospheric N₂O, 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-CO₂ 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.

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