Using modeling to design and evaluate transient open ocean iron enrichment for carbon sequestration

Richard T. Barber (rbarber@duke.edu; 252-504-7578)
Duke University
Marine Laboratory
135 Duke Marine Lab Road
Beaufort, NC 28516-9721

Fei Chai (fchai@maine.edu; 207-581-4317)
University of Maine
School of Marine Sciences
5741 Libby Hall
Orono, ME 04469-5741

Introduction

During the 1990s the rate of increase of CO_2 in the atmosphere was about 3.5 Pg C y^{-1}. Total emissions were 7.4 Pg C y^{-1}, so about 3.9 Pg C y^{-1} (52% of total emissions) were sequestered naturally. Of this, about 2.2 Pg C y^{-1} was absorbed by the oceans and 1.7 Pg C y^{-1} by the land (US DOE, 1999). The Kyoto Protocol of 1997 calls for a 34% reduction of emissions by 2050 and a reduction of 70% from the projected emissions at 2100. The major approach to emission reduction must, of course, be direct reduction, that is, putting in place technologies that release less carbon per unit of energy provided. It is also widely suggested by authoritative sources (for example, US DOE, 1999) that carbon sequestration enhanced by human management or engineering could contribute to the reduction of net emissions by removing additional CO_2 from the atmosphere.

One approach to engineered carbon sequestration is based on the concept of enhancing the natural biogenic sequestration of carbon in the ocean. Enhancing new primary productivity in the ocean by fertilization with iron has the potential to sequester carbon from the atmosphere in the deep ocean at very low cost. In this context, “deep” ocean refers to the waters below the main thermocline or pycnocline of the ocean. These waters are out of contact with the atmosphere for some period of time.

There are two significant drawbacks to the iron fertilization sequestration concept: 1) it has not been fully tested and 2) there are strong environmental objections to it. Relative to the first point, it is appropriate to emphasize that it is well established that a transitory iron addition to high-nitrate, low-chlorophyll (HNLC) waters increases new primary productivity with a proportional drawdown of inorganic carbon from the euphotic zone. *In situ* iron-enrichment experiments in both the Southern Ocean (Antarctic Ocean) (Boyd et al., 2000; Watson et al., 2000) and the equatorial Pacific Ocean (Martin et al., 1994; Coale et al., 1996; Lindley and Barber, 1998) have shown that transient addition of very low concentrations of iron to HNLC waters dramatically increases the productivity and growth of both small and large phytoplankton as well as the zooplankton that graze on both size classes (cf., Martin and Fitzwater, 1988; de Baar et al., 2000).

What is not yet well documented is the fate of the new primary productivity once it disappears from the euphotic zone (Ridgwell, 2000; Charette and Buesseler, 2000), i.e., how much of it is transported vertically to the deep ocean. In addition, logistic constraints on the length of time the research vessels can remain with the fertilized patch have limited these experiments to about 20 days. For this reason, these otherwise successful experiments in the equatorial Pacific and the Southern Ocean have been unable to resolve the full temporal pattern of carbon redistribution in response to iron fertilization.

Because of environmental concerns (Chisholm, 1995), to date there have been no additional *in situ* experiments to provide proof of concept or improve the design of the operational fertilization process. Ecosystem modeling provides an alternative means to test many of the engineering aspects of the fertilization process, such as size of the fertilization patch, concentration of iron and frequency and pattern of fertilization. Modeling also greatly expands the temporal and spatial domain of the ocean response that can be resolved. In addition, modeling the process allows many iterations to be carried out and reduces the number of *in situ* experiments that will be needed to evaluate the environmental safety of the concept.

Objective

The objective of the proposed project is to provide a mechanism to optimize the design of iron fertilization sequestration experiments in order to reduce the number of *in situ* experiments needed to evaluate its efficacy and environmental safety.

Approach

The approach of the proposed project is to use an existing, thoroughly tested and validated ocean ecosystem model developed for the equatorial Pacific Ocean to design and evaluate various iron fertilization strategies for sequestering carbon in the deep ocean.

Project Description

The model we propose to use in this project, developed over a period of about eight years, has been thoroughly tested and validated (Chai et al., 1996, 2000 and in press; Dugdale et al., in press). The model reproduces very well the monthly productivity variability of the equatorial Pacific during the past decade, including El Niño- and La Niña-driven variability. This ability of the model is important because La Niña-driven productivity increases are the result of enhanced iron being upwelled from the Equatorial Undercurrent (Barber et al., 1996).

The model consists of 10 compartments describing two size classes of phytoplankton and zooplankton, detrital nitrogen and detrital silicon, silicate, total CO_2 and two forms of dissolved inorganic nitrogen – nitrate (NO_3) and ammonium (NH_4) – which are treated separately, thus enabling division of primary production into new production and regenerated production. This 10-component biological model is coupled with a three-dimensional ocean circulation model based on the Modular Ocean Model (MOM) and forced with the Comprehensive Ocean Atmosphere Data Set (COADS) monthly wind and heat flux. One of the most important design issues regarding iron fertilization is the effect of vertical and horizontal mixing and advection on iron concentration or phytoplankton dispersal. The physical aspects of the MOM subroutine are very well worked out for the equatorial Pacific Ocean and have been validated by numerous investigators (Pacanowski and Philander, 1981; Toggweiler and Carson, 1995). The model is capable of reproducing the low-silicate, high-nitrate and low-chlorophyll (LSHNLC) conditions in the equatorial Pacific (Dugdale et al., in press).

In the eastern equatorial Pacific, iron-enrichment experiments are simulated by changing the photosynthetic efficiency and nutrient uptake kinetics in a given spatial domain (or patch). With this ecosystem model it is possible to investigate the physical, biological and geochemical consequences of varying the size of the enriched patch, the frequency and duration of enrichment.

The carbon cycle is linked to this ecosystem model through the consumption and remineralization of assimilated nutrients based upon the nitrogen changes in the water column by using Redfield stoichiometric ratios. To estimate the CO_2 gas exchange flux across the sea-air interface in this model, the partial pressure of CO_2 in the surface water is determined. Based on the thermodynamics of carbon chemistry, the CO_2 partial pressure can be determined by the total CO_2 (TCO_2) and total alkalinity (TA) concentrations. Instead of modeling the entire distribution of alkalinity in the water column, the alkalinity of only the surface box is determined by a statistical regional representation of salinity normalized alkalinity for the equatorial Pacific Ocean with surface water temperature between 20°C and 29°C (Feely et al., 1997; Millero et al., 1998).

Results

A preliminary iron enrichment model experiment was conducted to test the feasibility of this approach. Iron fertilization was simulated by changing three key biological parameters that are directly affected by iron (Lindley and Barber, 1998). The parameters are α (the initial slope of the photosynthetic rate versus irradiance at low irradiance levels), $K_{Si(OH)4}$ (the half-saturation concentration of silicate uptake by diatoms), and $\mu 2_{max}$ (the potential maximum specific diatom growth rate), all of which are terms in the regulation of silicate uptake by diatoms.

Within the first 5 days following the modeled iron fertilization, diatom biomass increased more than 30-fold. This increase is very similar in magnitude to that observed in the IronEx-2 experiment (Coale et al., 1996). The diatom population decreased sharply two weeks after iron fertilization because of depletion of silicate, increased mesozooplankton grazing on the diatoms and increased export via fecal pellets. Further analysis of the results of this preliminary iron fertilization experiment is needed to determine what proportion of the observed CO_2 drawdown is exported vertically in sinking diatoms, what proportion is removed horizontally by mixing and advection and what proportion is recycled in the euphotic zone.

Benefits

The preliminary model experiment suggests that ecosystem modeling should be further investigated for the design and evaluation of various iron fertilization strategies for sequestering carbon in the ocean. The benefit of this project is that fewer *in situ* iron fertilization experiments will be required to evaluate the efficacy and environmental safety of this process.

References

Barber, R.T., M.P. Sanderson, S.T. Lindley, F. Chai, J. Newton, C.C. Trees, D.G. Foley, and F.P. Chavez (1996) Primary productivity and its regulation in the equatorial Pacific during and following the 1991-1992 El Niño. *Deep-Sea Research II* 43: 933-969.

Boyd, P.W. et al. (2000) A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization. *Nature* 407: 695-702.

Chai, F., R.C. Dugdale, T.-H. Peng, F.P. Wilkerson and R.T. Barber (in press) One dimensional ecosystem model of the equatorial Pacific upwelling system, part I: model development and silicon and nitrogen cycle. *Deep-Sea Research II*.

Chai, F., S. T. Lindley and R. T. Barber (1996) Origin and maintenance of high nitrate condition in the equatorial Pacific. *Deep-Sea Research II* 43: 1031-1064.

Chai, F., S. T. Lindley, J. T. Toggweiler and R. T. Barber (2000) Testing the importance of iron and grazing in maintenance of the high nitrate condition in the equatorial Pacific Ocean, a physical-biological model study. In: *The Changing Ocean Carbon Cycle: A Midterm Synthesis of the Joint Global Ocean Flux Study, Int. Geosphere-Biosphere Prog. Book Ser.,* 4, R. B. Hanson, H. W. Ducklow and J. G. Field (eds.). Cambridge University Press, pp. 156-186.

Charette, M. A. and K. O. Buesseler (2000) Does iron fertilization lead to rapid carbon export in the Southern Ocean? *Geochem. Geophys. Geosys.* 1 (Research Letter), Paper number 2000GC000069 (Available at http://www.g-cubed.org).

Chisholm, S. W. (1995) The iron hypothesis: Basic research meets environmental policy. *Reviews of Geophysics* 33: 1277-1288.

Coale, K. H. et al. (1996) A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean. *Nature* 383: 495-501.

De Baar, H. J. W. and P. W. Boyd (2000) The role of iron in plankton ecology and carbon dioxide transfer of the global oceans. In: *The Dynamic Ocean Carbon Cycle: A Midterm Synthesis of the Joint Global Ocean Flux Study, Int. Geosphere Biosphere Prog. Book Ser.*, 5, R. B. Hanson, H. W. Ducklow and J. G. Field (eds.). Cambridge University Press, pp. 61-140.

Dugdale, R.C., R. Barber, F. Chai, T.H. Peng, and F.P. Wilkerson (in press) One dimensional model of the equatorial Pacific upwelling system, Part II: Sensitivity analysis and comparison with JGOFS EqPac data. *Deep-Sea Research II.*

Feely, R.A., R. Wanninkhof, C. Goyet, D.E. Archer, and T. Takahashi (1997) Variability of CO_2 distributions and sea-air fluxes in the central and eastern equatorial Pacific during the 1991-1994 El Niño. *Deep-Sea Research II* 44: 1851-1867.

Lindley, S. T. and R. T. Barber (1998) Phytoplankton response to natural and artificial iron addition. *Deep-Sea Research II* 45: 1135-1150.

Martin, J. H. and S. E. Fitzwater (1988) Iron deficiency limits phytoplankton growth in the northeast Pacific subantarctic. *Nature* 331: 341-343.

Martin, J. H. *et al.* (1994) Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean. *Nature* 371: 123-129.

Millero, F.J., K. Lee, and M. Roche (1998) Distribution of alkalinity in the surface waters of the major oceans. *Mar. Chem.* 60: 111-130.

Pacanowski, R. C., and S. G. H. Philander (1981) Parameterization of vertical mixing in numerical models of tropical oceans. *J. Phys. Oceanogr.* 11: 1443-1451.

Ridgwell, A. J. (2000) Climatic effect of Southern Ocean Fe fertilization: Is the jury still out? *Geochem. Geophys. Geosyst.* 1, Paper number 2000GC000120 (Available at http://www.g-cubed.org).

Toggweiler, J.R. and S. Carson (1995) What are upwelling systems contributing to the ocean's carbon and nutrient budgets? In: *Upwelling in the Ocean: Modern Processes and Ancient Records*, C. P. Summerhayes, K.-C. Emeis, M. V. Angel, R. L. Smith, and B. Zeitzschel (eds.). Wiley, pp. 337-360.

US Department of Energy. (1999) *Carbon Sequestration Research and Development*. Report of the Office of Science and Office of Fossil Energy of the US DOE (Available at http://www.ornl.gov/carbon_sequestration/).

Watson, A. J., D. C. E. Bakker, A. J. Ridgwell, P. W. Boyd and C. S. Law (2000) Effect of iron supply on Southern Ocean CO_2 uptake and implications for glacial atmospheric CO_2. *Nature* 407: 730-733.