

Report to Congress

Ocean Fertilization

The potential of ocean fertilization for climate change mitigation

Requested on page 636 of House Report 111-366 accompanying the fiscal year 2010 Consolidated Appropriations Act (P.L. 111-117).

Executive Summary

Page 636 of House Report 111-366 that accompanies the Consolidated Appropriations Act of 2010 (Public Law 111-117) calls for the National Oceanic and Atmospheric Administration (NOAA) to “provide a report on the potential of ocean fertilization for climate change mitigation” to the House and Senate Committees on Appropriation within 60 days of enactment of the Act. Climate change mitigation includes any efforts to reduce climate change including reducing emissions of heat-trapping gases and particles, and increasing removal of heat-trapping gases from the atmosphere.

The oceans contain about 50 times as much carbon dioxide (CO₂) as the atmosphere, comprising around 38,118 billion metric tons of carbon compared to 762 billion metric tons in the atmosphere. What allows the oceans to store so much CO₂ is the fact that when CO₂ dissolves in surface seawater, it reacts with a vast reservoir of carbonate ions to form bicarbonate ions. This reaction effectively removes the dissolved gas form of CO₂ from the surface water, allowing the water to absorb more gas from the overlying air. This process, in combination with large-scale ocean circulation, has resulted in the transfer of between a quarter and a third of human-induced emissions of CO₂ from the atmosphere into the ocean since the beginning of the industrial revolution. Ocean biology enhances the ocean’s ability to absorb CO₂ from the atmosphere as follows: plants in the ocean, mostly microscopic floating plants called phytoplankton, absorb CO₂ and nutrients when they grow, packaging them into organic material. Most of this organic material is consumed by other organisms and eventually recycled into CO₂ and nutrients near the surface. However, about 1-2% sinks into the deep ocean where it is converted back into CO₂ and nutrients by the action of bacteria. The resulting CO₂ and associated nutrients can remain out of contact with the atmosphere for hundreds of years, until ocean circulation brings the deep water to the surface and the cycle can begin again.

Recently, three U.S.-based companies have proposed fertilizing the ocean with iron and other essential nutrients to enhance the tendency of ocean biology to transfer CO₂ from the surface ocean to the deep ocean. These companies seek to deploy ocean fertilization as a climate change mitigation measure. In order for ocean fertilization to lead to climate change mitigation, three criteria must be met: (a) ocean fertilization must lead to increased growth of phytoplankton, packaging carbon and nutrients together into organic material; (b) this organic material must be transferred into the deep ocean so that it does not simply get recycled near the surface releasing its carbon back to the atmosphere; and (c) this transfer of carbon from the surface ocean to the deep ocean must result in a compensating transfer of carbon from the atmosphere into the surface ocean.

This report reviews two decades of ocean fertilization research that has focused primarily on adding the micronutrient iron to regions of the ocean that are iron-poor. A limited amount of research has focused on adding the nutrients nitrogen or phosphorus to areas that primarily lack those nutrients. However, since very small amounts of iron are required by phytoplankton to

make organic matter (1 atom for every 50,000 to 200,000 atoms of carbon) compared to the nutrients nitrogen (1 atom for every 16 atoms of carbon) or phosphorus (1 atom for every 106 atoms of carbon), iron fertilization has been seen as the most feasible approach for altering the ocean's carbon cycle on a significant scale and has been the focus of scientific and commercial interest in the United States. This report focuses on the potential for fertilizing the ocean with iron to lead to climate change mitigation.

Ocean fertilization research has made an extremely valuable contribution to the scientific understanding of the ocean carbon cycle and its role in the global carbon cycle on time scales ranging from glacial episodes thousands of years in the Earth's past to today's changing climate. All reported ocean fertilization experiments have resulted in increased growth of phytoplankton (criterion (a)). However, the resulting transfer of organic material from the surface ocean into the deep ocean (criterion (b)) and the compensating transfer of carbon into the ocean from the atmosphere (criterion (c)) have not been verified. Thus, the research undertaken to date has not demonstrated that ocean fertilization is a mature technology for climate change mitigation. Modeling studies also suggest that the maximum possible impact of ocean fertilization on atmospheric CO₂ concentrations is likely to be a small fraction of what is needed to stabilize CO₂ concentrations at twice the preindustrial concentration, a general target for avoiding catastrophic climate change.

There are also environmental risks associated with ocean fertilization. Adding nutrients to the ocean causes changes in the structure and functioning of marine ecosystems, and these changes may result in unintended negative consequences. Scientists hypothesize that such consequences may include: decreases in productivity in ocean regions remote from the fertilization site; alteration of the relative abundance, size structures and diversity of higher trophic levels, including (but not limited to) economically important species; increases in deep ocean hypoxia or anoxia; increases in the oceanic production of the greenhouse gases nitrous oxide and methane; generation of toxin-producing algae; introduction of toxic chemicals at the fertilization site (depending on the composition of the fertilization material); and increases in ocean acidification with associated increased impacts in sub-surface ecosystems already vulnerable to ocean acidification. Concern about the environmental consequences of proposed large-scale ocean fertilization experiments has triggered the development of an international regulatory mechanism through the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, to which the United States is a Party.

NOAA executed an agreement with the National Academy of Sciences to establish a committee on America's Climate Choices, as required under the Department of Commerce Appropriations Act of 2008 (Public Law 110-161). This committee established four expert panels, including a Panel on Limiting the Magnitude of Future Climate Change. The Panel has described, analyzed, and assessed strategies for reducing the net future human influence on climate, including both technology and policy options. The Panel's report, released on May 19 2010, provided Congress with information on a wide range of climate mitigation options. The present report assesses the

climate mitigation potential of a single proposed technology, ocean fertilization, as requested by Public Law 111-117.

I. Introduction

A. Definition of climate mitigation (including greenhouse gasses).

The House Report (111-366, page 636) that accompanies the Consolidated Appropriations Act of 2010 (Public Law 111-117) calls for the National Oceanic and Atmospheric Administration (NOAA) to “provide a report on the potential of ocean fertilization for climate change mitigation” to the House and Senate Committees on Appropriation within 60 days of enactment of the Act. Climate change mitigation includes any efforts to reduce climate change including reducing emissions of heat-trapping gases and particles, and increasing removal of heat-trapping gases from the atmosphere. Key findings of the U.S. Global Change Research Program¹ and the Intergovernmental Panel on Climate Change² provide the motivation for exploring climate mitigation approaches and technologies.

Observations show that warming of the climate is unequivocal. The global warming observed over the past 50 years is due primarily to human-induced emissions of heat-trapping gases. These emissions come mainly from the burning of fossil fuels (coal, oil, and gas), with additional contributions from the clearing of forests and agricultural activities. Heat-trapping gases include carbon dioxide, methane and nitrous oxide.

Climate-related changes have already been observed globally and in the United States. These include increases in air and water temperatures, reduced frost days, increased frequency and intensity of heavy downpours, a rise in sea level, and reduced snow cover, glaciers, permafrost, and sea ice. A longer ice-free period on lakes and rivers, lengthening of the growing season, and increased water vapor in the atmosphere have also been observed. Over the past 30 years, temperatures have risen faster in winter than in any other season, with average winter temperatures in the Midwest and northern Great Plains increasing more than 7°F. Some of the changes have been faster than previous assessments had suggested.

Warming over this century is projected to be considerably greater than over the last century. The global average temperature since 1900 has risen by about 1.5°F. By 2100, it is projected to rise another 2 to 10°F. The U.S. average temperature has risen by a comparable amount and is very likely to rise more than the global average over this century, with some variation from place to place. Several factors will determine future temperature increases. Increases at the lower end of this range are more likely if global heat-trapping gas emissions are cut substantially and/or

¹ Global Climate Change Impacts in the United States, Thomas R. Karl, Jerry M. Melillo, and Thomas C. Peterson, (eds.). Cambridge University Press, 2009.

² See, for example, IPCC, 2007: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

technologies are employed to remove heat-trapping gases from the atmosphere and store them in places that can remain out of contact with the atmosphere for centuries to millennia.

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B. How the ocean biosphere stores carbon dioxide.

The oceans store a vast amount of carbon dioxide (CO₂) in the forms of dissolved gas, carbonic acid, and carbonate and bicarbonate ions. The oceans currently contain about 50 times as much carbon dioxide as the atmosphere (around 38,118 GtC compared to 762 GtC in the atmosphere^{3,4}), and are estimated to have absorbed between a quarter and a third of human-induced emissions of CO₂ since the beginning of the industrial revolution.⁵ Of the 9.9 Gt of estimated global carbon emissions from fossil fuel burning and land use activities in 2008, 2.3±0.4 were absorbed by the ocean.⁶

The surface ocean absorbs CO₂ from the overlying air whenever its relative concentration (called its partial pressure) is higher in the air than it is in surface ocean water. Three factors make the

³ 1 GtC (gigaton of carbon) is one billion metric tons of carbon, or 2,204.6 billion pounds of carbon. To put this into perspective, 1 Gt is equivalent to about 143 million African elephants or 247 thousand US Capitol domes.

⁴ These numbers are from: Denman, K.L., *et al*, 2007: Couplings between changes in the climate system and biogeochemistry. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

⁵ This estimate for the total transfer of CO₂ into the ocean since the industrial revolution is derived from: Canadell, J.G., C. Le Quéré, M.R. Raupach, C.B. Field, E.T. Buitenhuis, P. Ciais, T.J. Conway, N.P. Gillett, R.A. Houghton, and G. Marland. 2007. Contributions to accelerating atmospheric CO₂ growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proc. Natl. Acad. Sci. USA* **104**, 18866-18870

⁶ Le Quéré, C., M.R. Raupach, J.G. Canadell, G. Marland, L. Bopp, P. Ciais, T. J. Conway⁶, S.C. Doney, R.A. Feely, P. Foster, P. Friedlingstein, K. Gurney, R.A. Houghton, J. I. House, C. Huntingford, P. E. Levy, M.R. Lomas, J. Majkut, N. Metzl, J. P. Ometto, G.P. Peters, I.C. Prentice, J.T. Randerson, S.W. Running, J.L. Sarmiento, U. Schuster, S. Sitch, T. Takahashi, N. Viogy, G.R. van der Werf, and F.I. Woodward. 2009. Trends in the sources and sinks of carbon dioxide. *Nature Geoscience* **2**: 831-836, DOI: 10.1038/NGEO689

ocean very effective at absorbing CO₂ from the atmosphere. The first factor is ocean chemistry. When CO₂ dissolves in surface sea water, it reacts with water and then with carbonate ions to form bicarbonate ions. These reactions effectively remove dissolved CO₂, lowering the partial pressure of CO₂ in the surface water and allowing the water to absorb more CO₂ from the overlying air. This process comes with a harmful side-effect, however, as the initial reaction with water forms a weak acid (carbonic acid), which reacts with carbonate ions thereby reducing carbonate ion concentrations. This decreased carbonate ion concentration makes those ions less available to the many marine organisms (such as corals and mollusks) that build their shells or skeletons out of calcium carbonate. This phenomenon is commonly referred to as ocean acidification. This effect of CO₂-linked ocean acidification may have deleterious impacts on marine ecosystems and their associated resources. NOAA scientists and their academic colleagues first quantified the impact of anthropogenic CO₂ on the calcium carbonate system in the global oceans in 2004⁷. Following the passage of the *Federal Ocean Acidification Research and Monitoring Act of 2009*, NOAA is establishing an ocean acidification program within the agency to conduct research and monitoring of ocean acidification and its impacts.

The second factor is large-scale ocean circulation. Seawater in major surface currents such as the Gulf Stream travels from the warm tropics to the cold Polar Regions, cooling as it goes. Carbon dioxide dissolves more readily in cold water than in warm water, so as the water cools, it accumulates CO₂. Eventually the water becomes cold and dense⁸ enough to sink to the bottom of the ocean, carrying accumulated CO₂ into the deep ocean circulation system, where it can remain out of contact with the atmosphere for hundreds of years. Much of this carbon-rich deep water returns to the surface in the Southern Ocean, where strong winds and weak stratification⁹ allow surface water and deep water to mix. Some remains in deep ocean currents, with a small fraction finally returning to the surface in the North Pacific, about 1600 years after it last had contact with the air in the North Atlantic. This ocean circulation system transfers CO₂ at today's concentrations into the deep ocean, removing it from contact with the atmosphere, while bringing waters to the surface that last had contact with the much lower CO₂ concentrations of the pre-industrial atmosphere. This exchange of old waters for new allows the entire ocean to participate in the chemical equilibration process described in the last paragraph, albeit on time scales of hundreds to thousands of years. NOAA scientists and their academic colleagues have

⁷ Feely, R.A., C.L. Sabine, K. Lee, W., Berelson, J. Kleypas, V.J. Fabry., and F.J. Millero. 2004. Impact of Anthropogenic CO₂ on the CaCO₃ System in the Oceans. *Science* 305 (5682), 362. [DOI: 10.1126/science.1097329]

⁸ Seawater density is determined by salinity and temperature, with saltier water being denser than less salty water, and colder water being denser than warmer water. Rain falling on the ocean can make surface water less salty and less dense, whereas evaporation or sea ice formation (when sea ice forms, only water freezes and the salt is left behind) make water more salty and more dense.

⁹ In most regions of the world's oceans, water is stratified with less dense water floating on top of water that is denser.

traced the penetration of anthropogenic CO₂ (the fraction of atmospheric CO₂ that is associated with human activities such as burning fossil fuels and changing land use) into the deep waters of the Atlantic, and the intermediate waters of the Southern Ocean.¹⁰ Oceanographers refer to the combined effect of ocean chemistry and ocean physics to transfer CO₂ from surface water to deep water as the “solubility pump.”¹¹

The third factor that makes the oceans so effective at absorbing CO₂ from the atmosphere is ocean biology. Just like trees do on land, plants in the ocean absorb CO₂ when they grow. In the open ocean, most of the plant growth is by microscopic floating plants called phytoplankton. Phytoplankton need CO₂, nutrients and sunlight to grow. They convert CO₂ and nutrients into organic matter, packaging carbon and nutrients together and forming the basis for marine food webs. Most of this organic matter is converted back to CO₂ and nutrients near the surface when the phytoplankton are eaten by zooplankton (tiny animals that drift with ocean currents) and other consumers. But approximately 15-20% sinks out of the surface water into intermediate-depth waters below and a small fraction of that (approximately 10% or 1-2% of the initial biological production) sinks into the deep ocean where it is converted back into CO₂ and nutrients by the action of bacteria.¹² This process effectively pumps CO₂ from surface waters into the deep ocean. Oceanographers call this process the “biological pump.” Carbon that is transferred into deep water by this process can remain out of contact with the atmosphere for hundreds of years. When deep waters enriched in nutrients and carbon return to the surface, the carbon stored there will escape back to the atmosphere unless phytoplankton take up the nutrients and carbon and begin the cycle again. Regions of unused nutrients thus represent locations where carbon stored in the ocean by the biological pump can leak back to the atmosphere.¹³

A useful analogy is to visualize the carbon stored in the deep ocean as water in a bath tub. The ocean carbonate system regulates the total size of the tub. The solubility pump and the biological pump are the faucets, adding water to the bath tub. The Southern Ocean, the

¹⁰ Sabine, C.L., R.A. Feely, N. Gruber, R.M. Key, K.Lee, J.L. Bullister, R. Wanninkhof, C.S. Wong, D.W.R. Wallace, B. Tilbrook, F.J. Millero, T.-S. Peng, A. Kozyr, T. Ono, and A.F. Rios. 2004. The Oceanic Sink for Anthropogenic CO₂. *Science* 305 (5682), 367. [DOI: 10.1126/science.1097403]

¹¹ Volk, T., and M.I. Hoffert (1985), Ocean carbon pumps: Analysis of relative strengths and efficiencies in ocean driven atmospheric CO₂ changes, in *The Carbon Cycle and Atmospheric CO₂: Natural Variations Archaean to Present*, Geophys. Monogr. Ser., vol. 32, edited by E. T. Sundquist and W. S. Broecker, pp. 99–110, AGU, Washington, D. C

¹² Dunne, J.P., J.L. Sarmiento, and A. Gnanadesikan, 2007: A synthesis of global particle export from the surface ocean and cycling through the ocean interior and on the seafloor. *Global Biogeochemical Cycles*, 21, GB4006, doi:10.1029/2006GB002907

¹³ Watson, A.J. and J.C. Orr. 2003. Carbon dioxide fluxes in the global ocean, in *Ocean Biogeochemistry: The role of the ocean carbon cycle in climate change*, Edited by M.J.R. Fasham, Springer-Verlag, pp. 123-144.

Equatorial and North Pacific Ocean and other regions where deep ocean water rich in nutrients and carbon returns to the surface act to drain the bath tub. Over time scales of thousands of years, the faucets and the drains will balance each other, so that the water in the bath tub remains level. The water level is currently rising because the increasing concentration of CO₂ in the atmosphere is acting like increased water pressure in the faucet that represents the solubility pump.

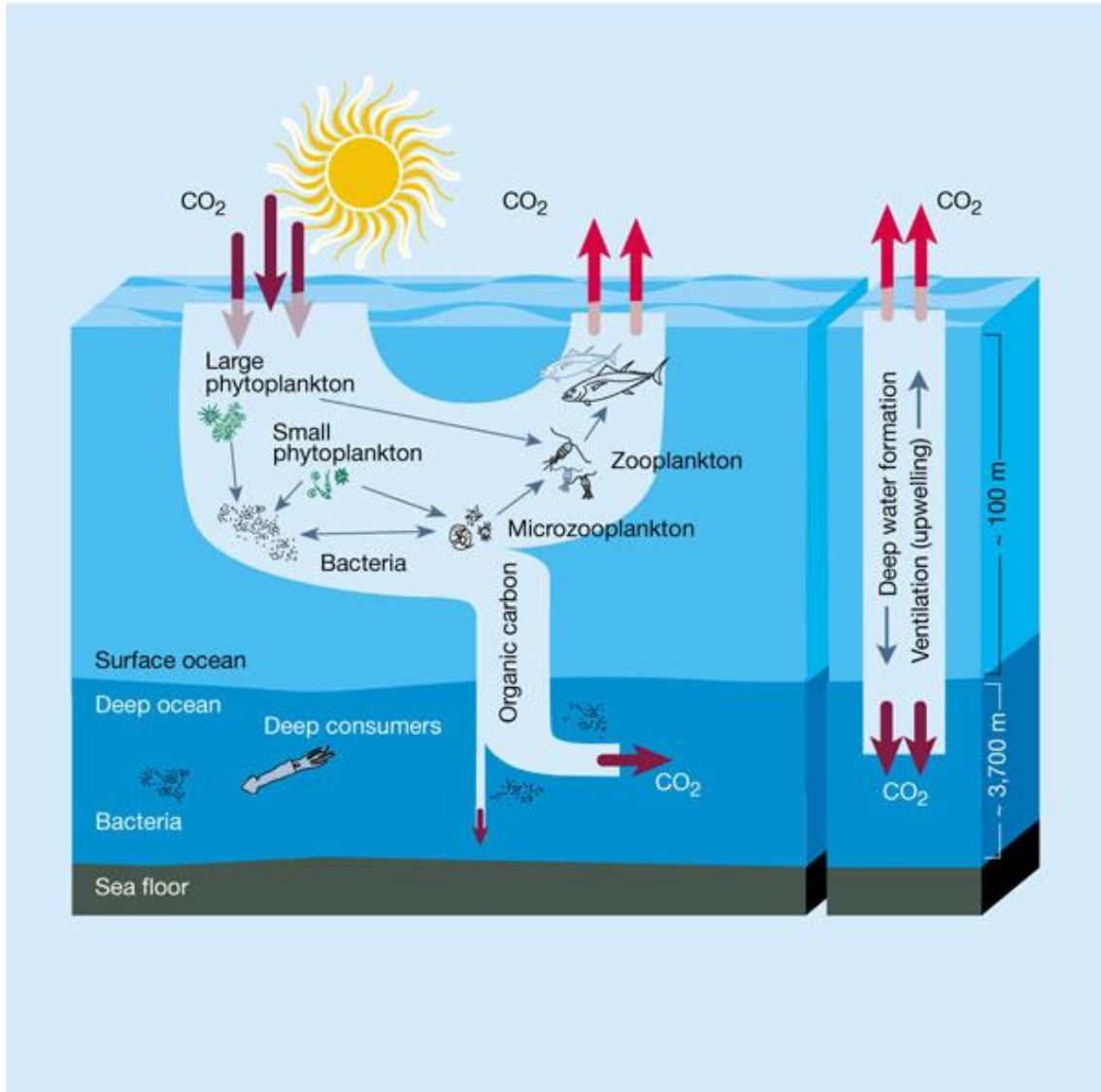


Figure 1. The ocean's biological pump (left) and solubility pump (right). Together these act to pump CO₂ from surface water into the deep oceans, where it can remain out of contact with the atmosphere for hundreds of years. The solubility pump is driven by ocean physics and chemistry, whereas the biological pump is driven by ocean biology. Phytoplankton need CO₂, nutrients and sunlight to grow. They convert CO₂ and nutrients into organic matter, packaging carbon and nutrients together and forming the basis for marine food webs. Most of this organic matter is converted back to CO₂ and nutrients near the surface when the phytoplankton are eaten by zooplankton (tiny animals that drift with ocean currents) and other consumers. But

approximately 1-2% sinks into the deep ocean where it is converted back into CO₂ and nutrients by the action of bacteria. Figure from Chisholm, S.W. 2000. Oceanography: Stirring times in the Southern Ocean. *Nature* 407: 685-687 doi:10.1038/35037696.

C. Why the ocean biosphere is inefficient at keeping carbon dioxide out of the atmosphere (nutrient limitation, light limitation)

Vast regions of the world's oceans appear to contain all the necessary ingredients for abundant plant life (light, carbon dioxide, and the essential nutrients phosphorus, nitrogen and silicon), and yet support only sparse populations of phytoplankton. Oceanographers call these regions High Nutrient Low Chlorophyll (HNLC) regions, and they can be found in the North Pacific, the Equatorial Pacific and the Southern Ocean. As noted above, these regions are places where carbon stored by biological cycling can escape from the ocean. Scientists on the 1925-1927 *Discovery* Expedition observed HNLC conditions in the Southern Ocean and wondered if "minute quantities of inorganic compounds, as iron or manganese, or of organic compounds derived from the land" might be necessary for abundant phytoplankton growth.¹⁴ The late American oceanographer, John Martin, hypothesized that the missing ingredient is iron. Iron is an essential component in many of the enzymes and pigments necessary for plant growth. While it is the fourth most abundant element in the Earth's crust, iron in the ocean is either rapidly removed from the surface ocean by sticking to sinking particles or binds to chemicals that make it difficult for most plankton to use.¹⁵ Martin's "iron hypothesis" is that phytoplankton in the HNLC regions suffer from iron deficiency, and this deficiency limits how much carbon those phytoplankton transfer from the surface ocean to the deep ocean via the biological pump. This hypothesis is supported by work (including seminal research by NOAA scientists) showing that the optimal iron concentration for laboratory cultures of phytoplankton is higher than concentrations usually found in the open ocean.¹⁶ Because plankton require very little iron (phytoplankton cells with sufficient iron generally contain 50,000-200,000 atoms of carbon for every atom of iron)¹⁷ a few hundred thousand tons of soluble iron supplied by dust and sediments are all that is required to support the approximately 10 billion tons of organic carbon leaving the

¹⁴ See comments on the 1925-1927 *Discovery* Expedition in Hardy, 1967, quoted by Martin, J.H. R.M. Gordon, 1988. Northeast Pacific iron distributions in relation to phytoplankton productivity. *Deep-Sea Research* 35:177-196

¹⁵ Rue, E.L. and K.W. Bruland, Complexation of iron(III) by natural organic ligands in the Central North Pacific as determined by a new competitive ligand equilibration / adsorptive cathodic stripping voltametric method, *Marine Chemistry*, 50, 117-138, 1995.

¹⁶ Sunda, W.G. and S.A. Huntsman, 1997: Interrelated influence of iron, light, and cell size on marine phytoplankton growth, *Nature*, 390, 389-392.

¹⁷ De Baar, H.J.W., L.J.A. Gerringa, P. Laan, and K.R. Timmermanns, 2008: Efficiency of carbon removal per added iron in ocean iron fertilization, *Mar. Ecol. Progr. Ser.*, 364. 269-282.

sunlit waters of the upper ocean each year.^{18,19} Were Martin's hypothesis correct, it would imply that relatively small quantities of iron would be required to enable phytoplankton to make full use of the surface nutrients in the HNLC regions, greatly enhancing the ocean's biological pump and slowing the escape of dissolved CO₂ into the atmosphere that occurs in these regions.

The fact that iron can limit growth does not, however, mean that it is the only or even the dominant factor preventing phytoplankton from growing and "pumping" carbon and nutrients into the deep ocean. Competing hypotheses are that phytoplankton growth is held in check by a lack of light, particularly in the Southern Ocean where strong winds can stir surface water to great depths, plunging phytoplankton into darkness,²⁰ or that phytoplankton are quickly consumed by a highly efficient food chain of tiny zooplankton and microbes, which constantly recycle the phytoplankton back to their constituent nutrients.²¹

Martin's original statement of the "iron hypothesis" was an effort to explain the changes in the concentration of carbon dioxide in the Earth's atmosphere from glacial levels (around 200 ppm²²) to the higher levels seen in warmer interglacial periods (around 280 ppm), a difference of around 170 GtC. Previous work had suggested that an increase in the biological pump, particularly in the Southern Ocean, could account for this change.²³ While vast regions of today's oceans, including the Southern Ocean are iron-deficient, the iron hypothesis states that the much windier and dustier atmospheres in glacial times blew iron-rich dust onto the ocean, allowing phytoplankton to thrive and enabling a much larger transfer of carbon and nutrients into the deep ocean by a much more efficient biological pump. As some of this carbon dioxide

¹⁸ Dunne, J.P., J.L. Sarmiento, and A. Gnanadesikan, 2007: A synthesis of global particle export from the surface ocean and cycling through the ocean interior and on the seafloor. *Global Biogeochemical Cycles*, 21, GB4006, doi:10.1029/2006GB002907

¹⁹ Estimates of the delivery of iron to the ocean by atmospheric dust range between 10 and 35 million tons but only a small fraction of this iron is soluble and thus available to plankton. See: Jickells, T. and L. Spokes, 2001: Atmospheric iron inputs to the ocean, in *The Biogeochemistry of Iron in Seawater*, edited by D.R. Turner and K.A. Hunter, pp. 85-121, John Wiley, NY.

²⁰ Mitchell, B.G., E.A. Brody, O. Holm-Hansen, C. McClain, and J. Bishop. 1991. Light limitation of phytoplankton biomass and macronutrient utilization in the Southern Ocean. *Limnology and Oceanography*, 36: 1662-1677

²¹ Frost, B.W. 1991. The role of grazing in nutrient-rich areas of the open sea. *Limnology and Oceanography*, 36: 1616-1630.

²² Concentrations of CO₂ in the atmosphere are typically reported in parts per million by volume, or ppm for short. 200 ppm means that for every million volumes of air, 200 consist of CO₂. For updated values of atmospheric CO₂ concentration, please see: <http://www.esrl.noaa.gov/gmd/ccgg/trends/index.html#global>

²³ Sarmiento J.L. and J.R. Toggweiler, 1984: A new model for the role of the oceans in determining atmospheric pCO₂, *Nature* 308,621-624.

comes out of the atmosphere, this could explain the large fluctuations in atmospheric carbon dioxide concentrations.²⁴ A competing hypothesis by J.R. Toggweiler is that the entire change in atmospheric CO₂ can be accounted for by a combination of three factors: an increase in the solubility of CO₂ in the colder surface waters of the glacial oceans; a decrease in the rate of return of deep water to the surface in the Southern Ocean due to changes in ocean circulation; and an increased capacity of the deep oceans to store CO₂ caused by adjustments in the calcium carbonate system.²⁵ To return to the bathtub analogy, Martin's hypothesis invokes an increase in the water being added to the tub by the biological pump faucet, whereas Toggweiler's hypothesis invokes the combination of an increase in the solubility pump faucet, a decrease in the Southern Ocean drain, and an increase in the size of the bathtub.

D. Proposals to increase this efficiency by adding macro/micro nutrients.

Although Martin's "iron hypothesis" was motivated by his desire to explain glacial-to-interglacial changes in atmospheric CO₂ concentrations, in the paper describing the hypothesis, Martin advocated testing the idea by performing "realistic large-scale iron enrichment experiments" in iron-deficient regions of the modern ocean.²⁶ In a subsequent paper, Martin and co-workers made the link between the iron hypothesis and climate change mitigation: "oceanic iron fertilization aimed at the enhancement of phytoplankton production may turn out to be the most feasible method of stimulating the active removal of greenhouse gas CO₂ from the atmosphere, if the need arises."²⁷ Martin made his most famous statement of the iron hypothesis not in a scientific paper but in a July 1988 seminar at the Woods Hole Oceanographic Institution: "I estimated that, with 300,000 tons of iron, the Southern Ocean phytoplankton could bloom and remove two billion tons of carbon dioxide. Putting on my best Dr. Strangelove accent, I suggested that with half a ship load of iron... I could give you an ice age."²⁸

Starting in 1993, an international community of oceanographers has tested the iron hypothesis in eleven open ocean iron addition experiments, and one experiment in which both iron and phosphorus were added to surface waters. The results of these experiments are summarized in Table 1 and are discussed in the next section. Other proposed ocean fertilization technologies include adding urea (a form of nitrogen) to nitrogen-starved areas of the ocean²⁹ and placing

²⁴ Martin, J.H. 1990. Glacial-Interglacial CO₂ Change: The Iron Hypothesis, *Paleoceanography*, 5(1), 1–13.

²⁵ Toggweiler, J.R. 1999. Variations of atmospheric CO₂ by ventilation of the ocean's deepest water. *Paleoceanography* 14: 571-588

²⁶ Martin, J.H. 1990. Glacial-Interglacial CO₂ Change: The Iron Hypothesis, *Paleoceanography*, 5(1), 1–13.

²⁷ Martin, J.H., R.M. Gordon, and S.E. Fitzwater. 1990. Iron in Antarctic waters. *Nature* 345: 156-158

²⁸ Martin, J.H. 1990. A new iron age, or a ferric fantasy. *U.S. JGOFS News* 1(4): 5, 11

²⁹ See Young E (2007) A drop in the ocean: Can dumping tonnes of fertiliser into the oceans really turn back the tide of global warming? *New Scientist*, September 15 2007, 42-45

vertical pipes in the ocean to pump nutrient-rich deep water to the surface in areas that are devoid of all plant nutrients.³⁰

Commercial interest in ocean fertilization technology began with the 1999 filing of US patent # 6,056,919 by Michael Markels, Jr., of Virginia-based GreenSea Venture. The patent is for a “Method of sequestering carbon dioxide” using iron and other fertilizers to enhance plant growth in the ocean. In the patent summary, Markels anticipated a market for carbon sequestration: “the governmental authority may allow credits on such balance sheet for the amount of carbon dioxide stated in such a report as being sequestered.” In 2002, Russ George of the Planktos Foundation³¹ fertilized a small patch of ocean near Hawaii³² in anticipation of a voluntary market for the sale of carbon credits. The other major venture in the area of iron fertilization is U.S.-based Climos, hoping to sell carbon credits on the regulated and unregulated emissions markets.³³ US-based Atmocean Inc. is designing pipes to pump cold, nutrient-rich deep water to the surface for carbon sequestration, fisheries enhancement and (by cooling the ocean surface) hurricane suppression.³⁴ Finally, Australia-based Ocean Nourishment Corporation seeks to commercialize urea fertilization (a form of nitrogen) for both carbon sequestration and fisheries enhancement.³⁵ Because far more nitrogen than iron is required for phytoplankton to make organic matter (roughly 1 atom of nitrogen for every 16 atoms of carbon, compared to 1 atom of iron for every 50,000 to 200,000 atoms of carbon), fertilizing the ocean with nitrogen is seen as far less feasible as compared to fertilizing the ocean with iron. Because of this, and because iron fertilization has been the most widely studied of the proposed ocean fertilization technologies, this report focuses on the potential for fertilizing the ocean with iron to lead to climate change mitigation.

³⁰ Lovelock J and C. Rapley. 2007. Ocean pipes could help the Earth to cure itself. *Nature* 449: 403. doi:10.1038/449403a

³¹ Now Planktos Science: <http://www.planktos-science.com>. Website accessed on 2 February 2009.

³² Schiermeier, Q. 2003. Climate change: The oresmen. *Nature* 421, 109-110 (9 January 2003) | doi:10.1038/421109a

³³ Whilden, K., M. Leinen, D. Whaley, and B. Grant. Ocean Fertilization as an Effective Tool for Climate Change Mitigation. in *IETA Greenhouse Gas Market Report 2007: Building Upon a Solid Foundation: The emergence of a global emissions trading system*. D. Lunsden, editor. International Emissions Trading Association, Geneva, Switzerland. 143 pp.

³⁴ Information from <http://www.atmocean.com/index.htm>, accessed on 2 February 2010. A report on an at-sea trial of the Atmocean pump technology is published as: White, A., K. Bjorkman, E. Grabowski, R. Letelier, S. Poulos, B. Watkins, and D. Karl. 2010. An open ocean trial of controlled upwelling using wave pump technology. *Journal of Atmospheric and Oceanic Technology*. 27: 385-396. doi: 10.1175/2009JTECHO679.1

³⁵ Glibert, P.M. et al (56 coauthors) 2008. Ocean urea fertilization for carbon credits poses high ecological risks. *Marine Pollution Bulletin* 56:1049–1056 doi:10.1016/j.marpolbul.2008.03.010

Experiment	Year	Location	Duration	Magnitude	Rationale/Hypothesis Tested	General Conclusions
IronEx I Martin et al., 1994	1993	Eastern equatorial Pacific Ocean	10 days	450 kg Fe 64 km ²	• Iron limitation of productivity in HNLC region	• Iron limits phytoplankton growth rate, but patch subducted; broader implications of OIF unclear
IronEx II Coale et al., 1996	1995	Eastern equatorial Pacific Ocean	17 days	450 kg Fe 72 km ²	• Iron limitation of productivity in HNLC region	• Iron definitively limits productivity in equatorial Pacific. Larger bloom than IronEx I
SOIREE Boyd et al., 2000	1999	Southern Ocean-Australia; South of Antarctic Polar Front (APF)	13 days	1740 kg Fe 50 km ²	• Iron limitation of productivity in Southern Ocean, south of the Antarctic Polar Front (APF) • Fate of carbon fixed in bloom	• Iron limits productivity in Southern Ocean • No downward carbon transport observed
EisenEx Smetacek, 2001; Assmy et al., 2007	2000	Southern Ocean-Africa; in APF zone	21 days	4 tonnes FeSO ₄ 38.5 km ²	• Iron limitation of productivity in Southern Ocean, along APF • Simulate Fe dust deposition to test whether Fe dust contributed to lower atmospheric CO ₂ concentrations during glacial periods	• Iron limits productivity in Southern Ocean • Fate of the bloom uncertain • Iron only affected certain species of phytoplankton
SEEDS-I Tsuda et al., 2005	2001	Subarctic Pacific-Northwest	13 days	350 kg Fe 80 km ²	• Iron limitation of productivity in HNLC of subarctic Pacific • Fate of carbon fixed in bloom	• Iron limits productivity in subarctic Pacific • Floristic shift to diatoms • Downward carbon export minimal
SOFEX-N SOFEX-S Coale et al., 2004; Buesseler et al., 2004	2002	Southern Ocean-New Zealand; north and south of APF	30 days	N: 1712 kg Fe 225 km ² S: 1260 Kg Fe 225 km ²	• Does OIF increase flux of carbon to deep ocean? • Silicate influence and geographic variability of response	• Increase in POC export flux, but magnitude is small relative to natural blooms
SERIES Boyd et al., 2004	2002	Subarctic Pacific-Gulf of Alaska	25 days	490 kg Fe 77 km ²	• Fate of carbon fixed in iron-induced bloom • Efficiency of carbon export to deep ocean	• Majority of carbon remineralized • Inefficient transport of carbon below thermocline
EIFEX Hoffmann et al., 2006; Jacquet et al., 2008	2004	Southern Ocean-Atlantic	35 days	7 tonnes FeSO ₄ 150 km ²	• Iron addition impacts on phytoplankton community structure • Carbon sequestration efficiency and remineralization rates	• Shift away from picophytoplankton • Majority of carbon fixed was not remineralized • Unpublished "massive carbon export" paper by Smetacek et al.
FeeP Rees et al., 2007; Karl and Letelier, 2008	2004	Sub-tropical Northeast Atlantic-LNLC	21 days	5 tonnes FeSO ₄ (+20 t PO ₄) 25 km ²	• Interaction between iron and phosphorus controls on biological activity in the subtropical North Atlantic	• Increased N-fixation activity was observed • No increase in primary productivity • Carbon export not measured
SAGE Law et al., 2006	2004	Southern Ocean-250 km from New Zealand	15 days	5.4 tonnes FeSO ₄ 100 km ²	• Iron addition's influence on sea-air gas exchange • CO ₂ drawdown and dimethylsulfide (DMS) production	• Doubling of chlorophyll <i>a</i> but no significant DMS production and no significant CO ₂ drawdown (preliminary results)
SEEDS-II Tsuda et al., 2007	2004	Subarctic Pacific-Northwest	26 days	491 kg Fe 64 km ²	• Monitor ultimate fate of bloom and carbon for longer time period than SEEDS-I	• No diatom bloom response • Increased zooplankton grazing
LOHAFEX NIO Press Release, 2009	2009	Southern Ocean-Atlantic	40 days	10 tonnes FeSO ₄ 300 km ²	• Ecological shifts and fate of sinking carbon	• Increased zooplankton grazing • Negligible carbon export (preliminary results)

Table 1: Summary of purposeful iron fertilization field experiments from: Strong, A.L., J. J. Cullen, and S.W. Chisholm. 2009. Ocean fertilization: Science, policy and commerce. *Oceanography Magazine* 22 (3):236- 261.

II. Iron fertilization experiments

The chemical and biological oceanography communities have been spurred by Martin's hypothesis to undertake a series of experiments where iron has been purposefully added to the ocean in various locations (Fig. 2, Table 1). Similar methods were used in most of the experiments: dissolved iron in the form of iron sulfate was mixed with seawater, an easy-to-measure inert tracer was added to allow the scientists to keep track of the fertilized water,³⁶ and the mixture was pumped into the ocean from a moving ship. Ships then monitored the fertilized patch of seawater for 10 to 40 days, comparing chemical and biological parameters from the fertilized patch and unfertilized water outside of the patch. Additionally, a number of experiments have explored the impacts of natural addition of iron to the ocean associated with particular natural features, such as the plume of dust coming off the Sahara, and sources of iron in the sediments of the Kerguelen plateau in the Southern Ocean. Because of the localized nature of these additions, it is possible to contrast regions that have received additional iron with adjacent regions that remain iron-poor, thus isolating the impact of iron fertilization. It should be emphasized that understanding the ocean's biological pump has not been the only motivation for these experiments: a significant motivation has also been to understand the role of iron in realistic ocean ecosystems. This is important as only a small fraction of ocean phytoplankton can be cultured in the laboratory, so it is by no means clear that responses found for individual species in the laboratory can represent responses of phytoplankton communities in nature. A list of purposeful ocean fertilization experiments is given in Table 1.

The questions examined in these field experiments include the following:

- A. Does adding iron allow phytoplankton to grow more rapidly and make better use of available light and other nutrients?
- B. Is this change associated with a change in the species of phytoplankton present at the fertilization site?
- C. Does this additional growth result in a net uptake of nutrients and carbon?
- D. Does the resulting "package" of carbon and nutrients (including iron) actually leave the surface ocean?
- E. Does fertilization result in other chemical changes in or near the fertilized region?

³⁶ In the report of IronEx I, the first open-ocean iron fertilization experiment, Martin and co-authors identified the development of the ability to measure ultra-trace concentrations of the inert gas sulfur hexafluoride, SF₆, as the major technological breakthrough that made ocean fertilization experiments possible by enabling the researchers to mark a patch of sea water and track it for long periods of time. See Martin, J.H. *et al.* 1994. Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean. *Nature* 371: 123-129 doi:10.1038/371123a0

Each of these questions is examined in the following subsections.

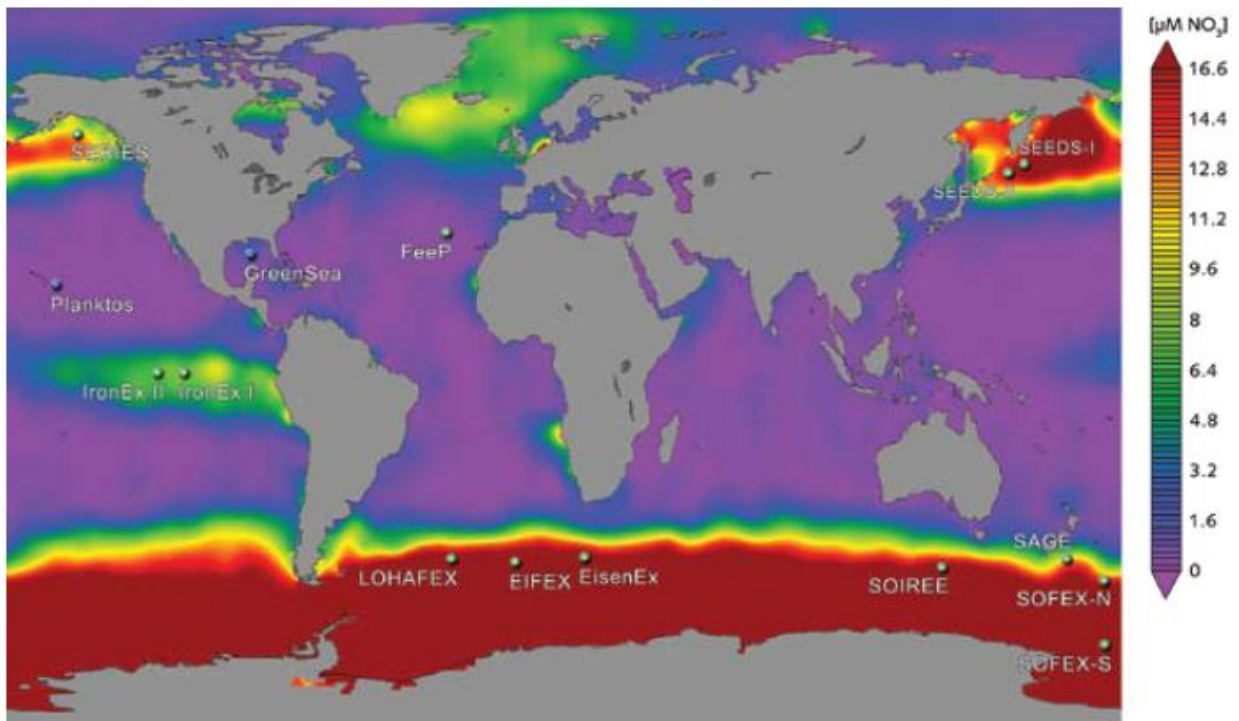


Figure 2. Locations of major iron fertilization experiments, including the pilot demonstrations of GreenSea Venture and Planktos. The color scale indicates the average annual surface nitrate concentration from the World Ocean Atlas 2005. Hotter colors indicate higher concentrations. The major HNLC regions in the Southern Ocean, the North Pacific and the Equatorial Pacific are clearly apparent as regions of high surface nitrate concentrations. Figure from Strong, A.L., J.J. Cullen and S.W. Chisholm, 2009. Ocean fertilization: science, policy and commerce. *Oceanography Magazine*, 22: 236-261.

A. Does adding iron allow phytoplankton to grow more rapidly?

The field experiments suggest that adding iron to HNLC regions of the ocean does make it easier for phytoplankton to grow. Increases in chlorophyll concentration in fertilized regions have been seen at all of the fertilization sites, indicating that iron does limit productivity in the equatorial Pacific, the Southern Ocean and the North Pacific. Measurements during a number of these experiments (including IronEx-II,³⁷ SOIREE,³⁸ and EisenEx³⁹) demonstrated that this increase

³⁷ Coale, K. H., K. S. Johnson, S. E. Fitzwater, R. M. Gordon, S. Tanner, F. P. Chavez, L. Ferioli, C. Sakamoto, P. Rogers, F. Millero, P. Steinberg, P. Nightingale, D. Cooper, W. P. Cochlan, M. R. Landry, J. Constantinou, G. Rollwagen, A. Trasvina and R. Kudela. 1996. The IronEx-II mesoscale experiment produces massive phytoplankton blooms in the equatorial Pacific. *Nature*, 383, 495-501.

³⁸ Boyd, P.W., A.J. Watson, C.S. Law, E.R. Abraham, T. Trull, R. Murdoch, D.C.E. Bakker, A.R. Bowie, K.O. Buesseler, H. Chang, M. Charette, P. Croot, K. Downing, R. Frew, M. Gall, M. Hadfield, J. Hall, M. Harvey, G.

was due to an improvement of the ability of phytoplankton to use more of the available light. During the SoFEX experiment an increase in the inherent growth rate of large and small plankton was seen as well.⁴⁰ The results support the idea that adding iron causes an increase in the biomass of phytoplankton because it allows them to grow faster, rather than that iron acts to inhibit grazing in some way. Thus, the field experiments support the idea that, in general, increasing iron allows marine plants to take up more carbon. Researchers failed to observe a change in the total biological uptake of carbon in only one of the experiments (FeeP). However, in two others (IronEx I⁴¹ and SoFEX⁴²) local currents appear to have limited the duration and magnitude of the bloom.

B. Is increased growth of phytoplankton associated with a change in the species of phytoplankton present at the fertilization site?

The current conceptual picture of ocean ecosystems proposes that they function in one of two modes. In ecosystems in which one or more necessary nutrients (e.g., nitrogen, phosphorus or iron) are scarce, phytoplankton growth is limited. Small phytoplankton which are more efficient at taking up nutrients tend to dominate, but their populations remain low because they are eaten by small zooplankton. Small zooplankton can reproduce very rapidly whenever the phytoplankton population grows, keeping the phytoplankton population in check. These “nutrient-limited” ecosystems are thought to export relatively little carbon and nutrients to the deep ocean, with most material being recycled in the surface ocean. In contrast, when nutrients are abundant, larger phytoplankton tend to dominate the system. These larger phytoplankton are eaten by larger zooplankton, which take longer to reproduce and are less efficient at keeping the phytoplankton population in check. These ecosystems are considered more productive than nutrient-limited ecosystem. Inefficient grazing by large zooplankton allows some phytoplankton to sink, carrying their constituent carbon and nutrients into the deep ocean. In addition, the

Jameson, J. LaRoche, M. Liddicoat, R. Ling, M.T. Maldonado, R.M. McKay, S. Nodder, S. Pickmere, R. Pridmore, S. Rintoul, K. Safi, P. Sutton, R. Strzepek, K. Tanneberger, S. Turner, A. Waite, J. Zeldis. 2000. A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization, *Nature*, 407, 695-702. doi:10.1038/35037500

³⁹ Gervais, F., U. Riebesell and M.Y. Gorbunov, 2002: Changes in primary productivity and chlorophyll *a* in response to iron fertilization in the Southern Polar Frontal Zone, *Limnol. Oceanogr.*, 47, 1324-1335.

⁴⁰ Hiscock, M.R., V.P. Lance, A. Apprill, R.R. Bidigare, Z.I. Johnson, B.G. Mitchell, W.O. Smith and R.T. Barber, 2008: Photosynthetic maximum quantum yield increases are an essential component of the Southern Ocean phytoplankton response to iron, *Proc. Natl. Acad. Sci.*, 105, 4775-4780.

⁴¹ Coale, K.H., K.S. Johnson, S.E. Fitzwater, S.P.G. Blain, T.P. Stanton and T.L. Coley, 1998: IronEx-I, An in-situ iron-enrichment experiment: Experimental design, implementation and results, *Deep Sea Res., Part II*, 919-945.

⁴² Krishnamurty, A., J.K. Moore and S.C. Doney, 2009: The effects of dilution and mixed layer depth on deliberate iron fertilization: 1-D simulations of the Southern Ocean Iron Experiment, (SOFeX), *J. Marine Systems*, 71, 112-130.

larger zooplankton and their predators (such as krill and small fish) tend to produce fecal pellets that sink rapidly, providing another means for pumping carbon and nutrients into the deep ocean.⁴³ Of particular interest in this respect are the large phytoplankton known as diatoms, which have for years been thought to play a disproportionately important role in highly productive marine ecosystems.⁴⁴ In this conceptual picture, adding iron to HNLC regions would be expected to change a nutrient-limited ecosystem into a more productive ecosystem, changing not only the amount of carbon taken up by phytoplankton, but the fraction of this carbon exported to the deep ocean.

The field experiments give moderate support to this picture. The IronEx II experiment saw a shift in species composition from small diatoms to large diatoms, with the genus *Pseudo-nitzschia* dominating.⁴⁵ The SOIREE experiment revealed a shift from small phytoplankton to diatoms after several days as did the EisenEx, SEEDS-1 and EIFEX experiments. However the SoFEX experiment saw all species increase in concentration and the SEEDS-II saw no diatom bloom response.

C. Does additional phytoplankton growth result in a net uptake of nutrients and carbon?

A larger uptake of carbon by phytoplankton does not necessarily imply a drawdown of surface nutrients- grazing of phytoplankton might simply recycle the organic matter back into inorganic form, thus failing to result in a net drawdown of nutrients and uptake of carbon. While the vast majority of iron fertilization experiments have shown clear drawdown of surface nutrients, the magnitude of this drawdown has varied greatly from experiment to experiment. For example, the SEEDS experiment in the North Pacific Ocean saw a drawdown of 15 micromole/kg, more than 80% of the initial nutrient concentration of 18 micromole/kg.⁴⁶ By contrast, during the SOFeX experiments⁴⁷ nitrate dropped by 2 micromole/kg within the fertilized patches, but this

⁴³ Dunne, J. P., J. L. Sarmiento, and A. Gnanadesikan, 2007: A synthesis of global particle export from the surface ocean and cycling through the ocean interior and on the seafloor. *Global Biogeochemical Cycles*, 21, GB4006, doi:10.1029/2006GB002907

⁴⁴ The role of diatoms was highlighted in Bigelow, H.B, 1924, Plankton of the offshore waters of the Gulf of Maine, *Bulletin of the Bureau of Fisheries*, Document 968, 486pp.,

⁴⁵ Landry, M.R., M.E. Ondrusek, S.J. Tanner, S.L. Brown, J. Constantinou, R.R. Bidigare, K.H. Coale and S. Fitzwater, 2000: Biological response to iron fertilization in the eastern equatorial Pacific (IronEx-II), I. Microplankton community abundances and biomass, *Mar. Ecol. Prog. Ser.*, 201, 27-42.

⁴⁶ Takeda, S. and A. Tsuda, 2005: An in situ iron enrichment experiment in the western subarctic Pacific (SEEDS): Introduction and summary, *Progress in Oceanography*, 64, 95-109.

⁴⁷ Coale, K.H., K. S. Johnson, F. P. Chavez, K. O. Buesseler, R. T. Barber, M. A. Brzezinski, W.P. Cochlan, F.J. Millero, P.G. Falkowski, J. E. Bauer, R. H. Wanninkhof, R.M. Kudela, M.A. Altabet, B.E. Hales, T. Takahashi, M. R. Landry, R.R. Bidigare, X. Wang, Z. Chase, P.G. Strutton, G.E. Friederich, M.Y. Gorbunov, V.P. Lance, A.K. Hiltling, M.R. Hiscock, M. Demarest, W.T. Hiscock, K.F. Sullivan, S.J. Tanner, R.M. Gordon, C.N. Hunter, V.A. Elrod, S.E. Fitzwater, J.L. Jones, S. Tozzi, M. Koblizek, A.E. Roberts, J. Herndon, J. Brewster, N. Ladizinsky, G.

drawdown represented only about 10% of the initial nutrient concentration. Insofar as this experiment captured the full potential of iron fertilization in this region (something that is by no means clear) it would suggest that iron fertilization would not in fact keep carbon from escaping this region. The reasons for such differences are still not well understood, though the SOFeX investigators suggested that temperature and light limitation might play an important role.

D. Does the resulting “package” of carbon and nutrients (including iron) actually leave the surface ocean?

If iron fertilization is to serve as a climate mitigation technology, it must do more than stimulate productivity: the biological pump of carbon must be enhanced or the leak of carbon from the deep ocean must be plugged. It is at this point that the picture becomes less clear. Some reduction of the oceanic dissolved CO₂ concentrations has been seen in field experiments suggesting that the fertilized patch of ocean should have been taking up carbon from the atmosphere. Most of the purposeful fertilization experiments (e.g. Iron-Ex-II⁴⁸, SOIREE⁴⁹, and SEEDS⁵⁰) found significant reductions (~20-60 ppm) in dissolved CO₂, though Iron-ExI specifically did not.⁵¹ However, the time taken for the dissolved CO₂ in surface ocean water to come to equilibrium with CO₂ in the overlying air is very long (approximately 1 year),⁵² so that the direct flux of carbon to the ocean that can be directly inferred from such experiments is actually very small. An alternative to measuring the flux from the atmosphere to the surface ocean would be to measure the cause of such a flux, i.e. the export of carbon from the surface ocean to the deep ocean. However measuring this flux has not proved straightforward either. As seen in Table 1, in the SOIREE, SEEDS-1, SoFeX-N and SoFeX-S, SAGE and LoHAFEX experiments, the additional carbon export due to fertilization appears to have been very small.

Smith, D. Cooper, D. Timothy, S.L. Brown, K.E. Selph, C.C. Sheridan, B.S. Twining, and Z.I. Johnson., 2004, Southern Ocean iron enrichment experiment: Carbon cycling in high- and low-Si waters, *Science*, 304, 408-414.

⁴⁸Cooper., D., A.J. Watson, and P.D. Nightingale, 1996: Large decrease in ocean-surface CO₂ fugacity in response to in situ iron fertilization, *Nature*, 383, 511-513.

⁴⁹ Bakker, D.C.E., A.J. Watson and C.S. Law, Southern Ocean iron enrichment promotes inorganic carbon drawdown, *Deep Sea Res. II*, 44, 91-127.

⁵⁰ Tsuda, A., S. Takeda, H. Saito, J. Nishioka, Y. Nojiri, I. Kudo, H. Kiyosawa, A. Shiimoto, K. Imai, T. Ono, A. Shimamoto, D. Tsumune, T. Yoshimura, T. Aono, A. Hinuma, M. Kinugasa, K. Suzuki, Y. Sohrin, Y. Noiri, H. Tani, Y. Deguchi, N. Tsurushima, H. Ogawa, K. Fukami, K. Kuma, and T. Saino. 2003. A mesoscale iron enrichment in the western subarctic Pacific induces a large centric diatom bloom, *Science* 300, 958-961.

⁵¹ Watson, A.J., C.S. Law, K.A. Van Scoy, F.J. Millero, W. Yao, G.E. Friederich, M.I. Liddicoat, R.H. Wanninkhof, R.T. Barber, and K.H. Coale. 1994. Minimal effect of iron fertilization on sea-surface carbon dioxide concentrations, *Nature* 371, 143-145.

⁵² Wanninkhof, R. and W.R. McGillis 1999: A cubic relationship between air-sea CO₂ exchange and wind speed, *J. Geophys. Res.*, 97, 7383-7382.

Only the (as yet unpublished) EIFEX experiment saw a massive bloom of mat-forming diatoms that carried a significant amount of carbon to depth. A synthesis of iron fertilization experiments published in 2005⁵³ found that the ratio of carbon exported to iron added ranged from 1700 to 35000, significantly smaller than the much higher carbon-to-iron ratios found in ocean plankton. This suggests that much of the iron added during ocean fertilization experiments is simply lost from the system. There are at least two possible explanations for the lack of observed carbon export. One is that the experiments were too small in scale and too short-lived. For example, during the SoFEX experiment, waters to which iron was added mixed with surrounding waters where iron and the concentration of organisms was much lower, leading to suggestions that this process prevented an intense bloom from developing.⁵⁴

A second explanation, however, is that phytoplankton blooms do not necessarily lead to high carbon export. Recent observational work at Bermuda suggests that higher phytoplankton production may simply lead to more zooplankton consuming the phytoplankton higher in the water column.⁵⁵ Additionally, a recent global study comparing the amount of carbon-based particles collected in ocean sediment traps with satellite observations of phytoplankton growing near the sea surface revealed that during seasons with phytoplankton blooms, the fraction of carbon exported into deep waters is typically half that of the fraction exported during seasons when there are no phytoplankton blooms.⁵⁶

E. Does fertilization result in other chemical changes in or near the fertilized region?

Ocean biology does more than just take up carbon. Diatoms in particular are thought to be sources of dimethylsulphide (DMS), an important gas that when released into the atmosphere, enhances cloud formation over the oceans. These clouds reflect sunlight and can exert a regional cooling effect. In addition, the cycling of organic matter back to its constituent carbon and nutrient can produce nitrous oxide and possibly methane as well, both of which are greenhouse

⁵³ De Baar, H.J.W., P.W. Boyd, K.H. Coale, M.R. Landry, A. Tsuda, P. Assmy, D.C.e. Bakker, Y. Bozec, R.T. Barber, M.A. Brzezinski, K.O. Buesseler, M. Boyé, P.L. Croot, F. Gervais, M.Y. Gorbunov, P.J. Harrison, W.T. Hiscock, P. Laan, C. Lancelot, C.S. Law, M. Lavoisier, A. Marchetti, F.J. Millero, J. Nishioka, Y. Nojiri, T. van Oijen, U. Riebesell, M.J.A. Rijkenberg, H. Saito, S. Takeda, K.R. Timmermans, M.J.W. Veldhuis, A.M. Waite, C.-S. Wong. 2005. Synthesis of iron fertilization experiments: From the Iron Age in the Age of Enlightenment, *J. Geophys. Res.*, 110, C09S16, doi:10.1029/2004JC002601.

⁵⁴ Hiscock, W.T. and F.J. Millero, Nutrient and carbon parameters during the Southern Ocean iron experiment, SOFEX, *Deep Sea Res. I.*, 52 2086-2108.

⁵⁵ Lomas, M. W., D.K. Steinberg, T. Dickey, C.A. Carlson, N.B. Nelson, R.H. Condon and N.R. Bates. Increased ocean carbon export in the Sargasso Sea linked to climate variability is countered by its enhanced mesopelagic attenuation, *Biogeosciences*, 7, 57-70, doi:10.5194/bg-7-57-2010, 2010.

⁵⁶ Lutz, M.J., K. Caldeira, R. B. Dunbar, and M. J. Behrenfeld (2007), Seasonal rhythms of net primary production and particulate organic carbon flux to depth describe the efficiency of biological pump in the global ocean, *J. Geophys. Res.*, 112, C10011, doi:10.1029/2006JC003706.

gases with much higher heat trapping potential than CO₂. Accordingly, a number of experiments have looked for such changes, with ambiguous results. For example, the SOIREE experiment found a tripling in DMS concentration over a two week period, but the SAGE experiment found no such change.

Certain species of diatoms are known to produce domoic acid, a neurotoxin associated with harmful algal blooms.⁵⁷ Iron enrichment experiments have generated large diatom blooms that in most cases are dominated by diatoms belonging to the genus *Pseudo-nitzschia*, including studies conducted in the northwest Pacific (SEEDS II),⁵⁸ northeast Pacific (SERIES),⁵⁹ equatorial Pacific (IronEx II),^{60,61} and the Southern Ocean (SOIREE,⁶² EisenEx,⁶³ SoFeX,^{64,65} and Eifex⁶⁶)

⁵⁷ Trainer, V.L., B.M. Hickey, and S.S. Bates. 2008. Diatoms.. In: Walsh, P.J., S.L. Smith, L.E. Fleming, H. Solo-Gabriele, W.H. Gerwick (eds.). *Oceans and Human Health: Risks and Remedies from the Sea*, pp.219-238. Elsevier Science Publishers, New York.

⁵⁸ Tsuda, A., S. Takeda, H. Saito, J. Nishioka, I. Kudo, Y. Nojiri, K. Suzuki, M. Uematsu, M.L. Wells, D. Tsumune, T. Yoshimura, T. Aono, T. Aramaki, W.P. Cochlan, M. Hayakawa, K. Imai, T. Isada, Y. Iwamoto, W.K. Johnson, S. Kameyama, S. Kato, H. Kiyosawa, Y. Kondo, M. Levasseur, R.J. Machida, I. Nagao, F. Nakagawa, T. Nakanishi, S. Nakatsuka, A. Narita, Y. Noiri, H. Obata, H. Ogawa, K. Oguma, T. Ono, T. Sakuragi, M. Sasakawa, M. Sato, A. Shimamoto, H. Takata, C.G. Trick, Y.W. Watanabe, C.-S. Wong and N. Yoshie. 2007. Evidence for the grazing hypothesis: Grazing reduces phytoplankton responses of the HNLC ecosystem to iron enrichment in the western subarctic Pacific (SEEDS II). *J. Oceanogr.* 63:983-994.

⁵⁹ Marchetti A, N.D. Sherry, H. Kiyosawa, A. Tsuda and P.J. Harrison. 2006. Phytoplankton processes during a mesoscale iron enrichment in the NE subarctic Pacific: Part I -biomass and assemblage. *Deep-Sea Res. Part II.* 53:2095-2113.

⁶⁰ Chisholm S.W., P.G. Falkowski and J.J. Cullen. 2001. Dis-crediting ocean fertilization. *Science* 294:309-310.

⁶¹ Coale K.H., K.S. Johnson, S.E. Fitzwater, R.M. Gordon, S. Tanner, F.P. Chavez, L. Ferioli, C. Sakamoto, P. Rogers, F. Millero, P. Steinberg, P. Nightingale, D. Cooper, W.P. Cochlan, M. R. Landry, J. Constantinou, G. Rollwagen, A. Trasvina, and R. Kudela. 1996. A massive phytoplankton bloom induced by an ecosystem scale iron fertilization experiment in the equatorial Pacific. *Nature* 383:495-501.

⁶² Boyd, P.W., A.J. Watson, C.S. Law, E.R. Abraham, T. Trull, R. Murdoch, D.C.E. Bakker, A.R. Bowie, K.O. Buesseler, H. Chang, M. Charette, P. Croot, K. Downing, R. Frew, M. Gall, M. Hadfield, J. Hall, M. Harvey, G. Jameson, J. LaRoche, M. Liddicoat, R. Ling, M.T. Maldonado, R.M. McKay, S. Nodder, S. Pickmere, R. Pridmore, S. Rintoul, K. Safi, P. Sutton, R. Strzepek, K. Tanneberger, S. Turner, A. Waite, J. Zeldis. 2000. A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization. *Nature* 407:695-702.

⁶³ Gervais F, U. Riebesell and M.Y. Gorbunov. 2002. Changes in primary productivity and chlorophyll a in response to iron fertilization in the Southern Polar Frontal Zone. *Limnol. Oceanogr.* 47:1324-1335.

⁶⁴ Coale, K.H., K. S. Johnson, F. P. Chavez, K. O. Buesseler, R. T. Barber, M. A. Brzezinski, W.P. Cochlan, F.J. Millero, P.G. Falkowski, J. E. Bauer, R. H. Wanninkhof, R.M. Kudela, M.A. Altabet, B.E. Hales, T. Takahashi, M. R. Landry, R.R. Bidigare, X. Wang, Z. Chase, P.G. Stratton, G.E. Friederich, M.Y. Gorbunov, V.P. Lance, A.K. Hiltling, M.R. Hiscock, M. Demarest, W.T. Hiscock, K.F. Sullivan, S.J. Tanner, R.M. Gordon, C.N. Hunter, V.A. Elrod, S.E. Fitzwater, J.L. Jones, S. Tozzi, M. Koblizek, A.E. Roberts, J. Herndon, J. Brewster, N. Ladizinsky, G.

The SERIES experiment demonstrated that while fertilization favored *Pseudo-nitzschia*, the phytoplankton genus that can produce domoic acid, detectable levels of this toxin were not found. However, a cruise in the same oceanographic area as SERIES (Ocean Station PAPA) has shown that oceanic *Pseudo-nitzschia* can produce measurable levels of toxin in its natural state and in response to iron addition experiments onboard ship and that domoic acid alters the phytoplankton community structure to benefit *Pseudo-nitzschia*.^{67,68,69} These results illustrate the still primitive state of understanding of how communities of phytoplankton actually behave and suggest that the consequences of ocean fertilization are still poorly known. Moreover, as some harmful algal blooms have been associated with the occurrence of excess nutrients in coastal waters,⁷⁰ the threat of harmful algal blooms remains a concern for certain applications of iron fertilization, particularly near the coast.

III. Models of iron fertilization

Evaluating the potential of iron fertilization for climate mitigation requires more than determining whether it can increase the biological pump of carbon and nutrients to the deep ocean. In fact a number of additional questions must be answered:

A. Can ocean fertilization take up enough carbon from the atmosphere have a mitigating effect on climate change?

B. Does exporting organic carbon to the deep ocean in a localized area lead to a net flux of carbon from the atmosphere to the ocean?

Smith, D. Cooper, D. Timothy, S.L. Brown, K.E. Selph, C.C. Sheridan, B.S. Twining, and Z.I. Johnson., 2004, Southern Ocean iron enrichment experiment: Carbon cycling in high- and low-Si waters, *Science*, 304, 408-414.

⁶⁵ Peloquin J.A. and W.O. Smith 2006. The role of phytoplankton size on photochemical recovery during the southern ocean iron experiment. *J. Phycol.* 42:1016-1027.

⁶⁶ Hoffmann L.J., I. Peeken and K. Lochte 2006. Different reactions of Southern Ocean phytoplankton size classes to iron fertilization. *Limnol. Oceanogr.* 51:1217-1239

⁶⁷ Trick, C.G., B.D. Bill, W.P. Cochlan, M.L. Wells, V.L. Trainer, and L.P. Pickell. 2009. Iron enrichment stimulates toxic diatom production in the High Nitrate Low Chlorophyll eastern Subarctic Pacific. Fifth Symposium on Harmful Algae in the U.S., Ocean Shores, WA, November 2009.

⁶⁸ Trick, C.G., B.D. Bill, W.P. Cochlan, M.L. Wells, V.L. Trainer, V. L., and L.P. Pickell. 2009. Understanding complexities in the induction of toxic algal blooms: Domoic acid. GEOHAB: Second Open Science Meeting on Harmful Algal Blooms and Eutrophication, Beijing, China, October 2009.

⁶⁹ Trick, C.G., B.D. Bill, W.P. Cochlan, M.L. Wells, V.L. Trainer, and L.P. Pickell. Iron enrichment stimulates toxic diatom production in High Nitrate Low Chlorophyll areas. *Proc. Nat. Acad. Sci.* In press..

⁷⁰ Glibert, P.A., J. Harrison, C. Heil and S. Seitzinger, 2006: Escalating worldwide use of urea- A global change contributing to coastal eutrophication, *Biogeochemistry*, 77, 441-463.

C. Can the flux of carbon from the atmosphere to the ocean be reliably quantified?

D. Are there undesirable consequences of fertilization?

All of these questions involve spatial scales that are much larger and time scales that are much longer than those associated with individual fertilization experiments. This means that the only way to address them is to use models to extrapolate from these specific results to the global scale. The following subsections introduce the models used to address these questions, and then treat each of them sequentially.

A. Modeling ocean circulation and biology

The first computer models of the ocean circulation were developed by NOAA scientists during the late 1960s,⁷¹ and similar models are now used by hundreds of oceanographers and climate scientists around the world. These models predict the circulation based on the conservation of heat, salt and momentum. Dividing the ocean up into millions of boxes, each of which contains some quantity of heat, salt, and momentum, an ocean model computes the forces that result from this distribution and uses these forces to generate a flow field. This flow field moves the heat, salt and momentum around, which then changes the driving forces of the flow. The current generation of ocean models are presently able to simulate the observed distributions of temperature and salt with reasonably good accuracy, so that the average temperature error over a box 100km on a side can be less than 1°C. They are also capable of simulating the distribution of trace gases, suggesting that they have relatively realistic rates of circulation.⁷²

Models of ocean ecosystems and carbon cycling were embedded within these circulation models starting in the late 1980s.⁷³ The earliest models were extremely primitive. Seeking to reconstruct the patterns of biological activity that could produce the observed patterns of nutrients, they simply represented the effect of biology as taking up nutrients at some rate that depended on the local nutrient concentration, ignoring the details of how phytoplankton and their associated ecosystems actually respond to iron and iron cycling. Models that actually tried to predict plankton concentrations were included in the comprehensive physical models during the

⁷¹ Bryan, K. and M.D. Cox, 1967. A numerical investigation of the oceanic general circulation, *Tellus*, 19, 54-80.

⁷² Matusmoto, K., J.L. Sarmiento, R.M. Key, O. Aumont, J.L. Bullister, K. Caldeira, J.M. Campin, S.C. Doney, H. Drange, J.C. Dutay, M. Follows, Y. Gao, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, K. Lindsay, E. Maier-Reimer, J.C. Marshall, R.J. Matear, P. Monfray, R. Najjar, G.K. Plattner, R. Schlitzer, R. Slater, P.S. Swathi, I.J. Totterdell, M.F. Weirig, Y. Yamanaka, A. Yool and J.C. Orr. 2004. Evaluation of ocean carbon cycle models with data-based metrics, *Geophys. Res. Lett.*, 31, L07303, doi:10.1029/2003GL018970.

⁷³ Najjar, R.G. 1990. Simulations of the phosphorus and oxygen cycles in the world ocean using a general circulation model, Ph.D. Thesis, Princeton Univ.

early 1990s⁷⁴ but did not in general include the impact of iron explicitly. It is only during the last decade that models with an explicit iron cycle that also resolve the impact of iron on different groups of plankton have emerged,⁷⁵ and these models still differ markedly from each other in terms of how they represent the impact of iron on ecosystems. These differences reflect significant scientific uncertainties as to how much soluble iron is delivered to the ocean, how it cycles chemically within the ocean, and what impact it has on changing the structure of ecosystems. Thus, while such models can be used to examine the interplay of different processes, their predictions are only as accurate as the biological and chemical dynamics that they encode. Researchers at a number of NOAA labs are trying to understand and model these fundamental dynamics which have implications for ecosystem structure and oceanic carbon uptake. However, it must be emphasized that many significant questions persist.

B. How much carbon uptake can ocean fertilization produce, and how rapidly?

As described above, the amount of carbon stored by the ocean depends both on how much carbon is injected into the deep ocean and how quickly it leaks out in HNLC regions. Insofar as iron fertilization acts to enhance the ocean's biological pump, it can increase the ocean carbon inventory only as fast as the natural rate of leakage, which in turn depends on the details of the ocean circulation. The first model study to examine this question with a comprehensive general circulation model was by Sarmiento and Orr,⁷⁶ using the Geophysical Fluid Dynamics Laboratory (GFDL) ocean general circulation model. This study assumed that iron fertilization would permit all nutrients brought to the surface to be used up, and then computed the impact on atmospheric CO₂. It was found that over 100 years, the ocean could take up a maximum of around 98-181 GtC, almost all of which was due to uptake in the Southern Ocean, south of 30 degrees south latitude. The maximum decrease in atmospheric CO₂ concentration because of this carbon uptake was calculated to range from 46 to 85 ppm over the course of a century. This is smaller than the 100 ppm increase in CO₂ since the beginning of the Industrial Revolution. Another recent paper by Cao and Caldeira found that under a "business as usual" emissions scenario, a global scale drawdown of surface nutrients could reduce atmospheric CO₂

⁷⁴ Sarmiento, J.L., R.D. Slater, M.J. Fasham, H.W. Ducklow, J.R. Toggweiler, and G.T. Evans. 1993. A seasonal three-dimensional ecosystem model of nitrogen cycling in the North Atlantic euphotic zone. *Global Biogeochemical Cycles*, 7(2), 417-450.

⁷⁵ Examples include Moore, J.K., S.C. Doney and K. Lindsay. 2004. Upper ocean ecosystem dynamics and iron cycling in a global 3-D model, *Global Biogeochemical Cycles*, 18, GB4028, doi:10.1029/2004GB002220. Aumont, O. and L. Bopp. 2006. Globalizing results from in-situ iron fertilization studies, *Global Biogeochemical Cycles*, 20, GB2017, doi:10.1029/2005GB002591, Galbraith, E.D., A. Gnanadesikan, J.P. Dunne and M.R. Hiscock. 2009. Regional impacts of iron-light collimitation in a global biogeochemical model, *Biogeosciences Discussions*, 5, 7517-7564.

⁷⁶ Sarmiento, J.L. and J.C. Orr. 1991. Three-dimensional simulations of the impact of Southern Ocean nutrient depletion on atmospheric CO₂ and ocean chemistry, *Limnol. Oceanogr.* 36, 1928-1950.

concentrations in the year 2100 from 965 ppm to 833 ppm.⁷⁷ Some of the difference between these two estimates arises from the fact that fertilization becomes more effective at removing carbon from the atmosphere as atmospheric CO₂ concentrations rise.

These model estimates of a potential atmospheric CO₂ reduction of up to 133 ppm represent an upper bound, unless major changes in ocean chemistry are allowed. More recent results⁷⁸ suggest that the region with the greatest leverage on atmospheric CO₂ concentrations is not the whole Southern Ocean, but rather the polar ocean around the Antarctic continent, because this is the region where unused nutrient levels are highest.⁷⁹ However, it is not clear how much of this leverage could in fact be realized, as these regions are dark during the wintertime and experience relatively low light levels even during the summer months. As a result, some models⁸⁰ show very little impact on atmospheric CO₂ from Southern Ocean fertilization. Other model studies that allow iron to change the ability of phytoplankton to make chlorophyll (the molecule responsible for harvesting light) have higher carbon uptake over a 100 year period. Aumont and Bopp⁸¹ find a drawdown of 33 ppm over 100 years, though they note that in their simulations some nutrients remain at the surface throughout the year in the Southern Ocean. Using a similarly comprehensive biological model including an iron cycle, Sarmiento and co-workers⁸² find an atmospheric drawdown of 35.3 ppm from Southern Ocean fertilization and 41.8 ppm from global fertilization over 100 years. It must be emphasized that these scenarios presuppose an infrastructure much more extensive than John Martin's "ship-load of iron;" they assume that millions of square kilometers of ocean are continually fertilized over hundreds of years, a feat that would be impractical if not impossible.

C. Local export and global uptake

One aspect of ocean fertilization revealed by models is that there is a big difference between increasing the export of carbon from the ocean surface locally and actually storing more carbon

⁷⁷ Cao, L., and K. Caldeira. 2010. Can ocean iron fertilization mitigate ocean acidification? *Climatic Change*, doi:10.1007/s10584-010-9799-4.

⁷⁸ Marinov, I., A. Gnanadesikan, J.R. Toggweiler and J.L. Sarmiento. 2006. The Southern Ocean biogeochemical divide, *Nature*, 441, doi:10.1038/nature04883/

⁷⁹ Gnanadesikan, A. and I. Marinov. 2008. Export is not enough: Nutrient cycling and carbon sequestration, *Mar. Ecol. Prog. Series*, 364, 289-294.

⁸⁰ Parekh, P., M.J. Follows, S. Dutkiewicz and T. Ito. 2006. Physical and biological regulation of the soft tissue carbon pump, *Paleoceanography*, 21,PA3001, doi:10.1029/2005PA001258.

⁸¹ Aumont, O. and L. Bopp. 2006. Globalizing results from in-situ iron fertilization studies, *Global Biogeochemical Cycles*, 20, GB2017, doi:10.1029/2005GB002591

⁸² Sarmiento, J.L., R.D. Slater, J.P. Dunne, A. Gnanadesikan and M.R. Hiscock. 2009. Efficiency of small-scale carbon mitigation by patch iron fertilization, *Biogeosciences Discussions*, 6, 10381-10446.

in the ocean on a global scale. Just as stopping up one leak in a very leaky bathtub may simply divert the outflow to a different hole, fertilizing one part of the ocean and drawing carbon into it at that location may lead to an increase in the flux out of the ocean elsewhere. Negative feedbacks of this sort reduce the efficiency of iron fertilization as a climate mitigation mechanism.

One important negative feedback acts through the uptake of anthropogenic CO₂. Models predict that over time scales of thousands of years, the world's oceans will take up 80% of global CO₂ emissions from fossil fuel use and land use activities.⁸³ Viewed in this way, it becomes clear that fertilizing the ocean to take up carbon now will result in a trade off of reduced ocean carbon uptake in the future. This effect is significant, compensating about 40% of the potential oceanic uptake of carbon over a course of a century.⁸⁴

A second potential negative feedback arises because iron fertilization may simply concentrate production at one point in space and time rather than increasing it overall. If one imagines a row of faucets, all drawing from the same pipe, gushing into a bathtub, opening an additional faucet may simply cause the flow to redistribute itself amongst the faucets. This appears to be particularly important in tropical regions where the carbon escapes the ocean along the equator as nutrient- and carbon-rich waters are brought to the surface and warmed, but re-enter the ocean off-equator as biological cycling takes up these nutrients and with them, CO₂.

A third negative feedback involves changes in the ratio of carbon to nutrients within phytoplankton. This is based on the observation that Southern Ocean diatoms are actually less efficient at packaging carbon with other nutrients than are other plankton.⁸⁵ While this mechanism has been proposed in the scientific literature,⁸⁶ its magnitude has not been tested with realistic models.

A final negative feedback involves the cycling of nitrogen. As organic material sinks to depth and decomposes it consumes oxygen. If ocean fertilization is to sequester carbon in the deep ocean it must also reduce deep ocean oxygen concentrations. Such reductions, particularly on

⁸³ Archer, D.A. 2005. Fate of fossil fuel CO₂ in geologic time. *J. Geophys. Res.* VOL. 110, C09S05, doi:10.1029/2004JC002625, 2005

⁸⁴ Gnanadesikan, A., J.L. Sarmiento and R.D. Slater. 2003. Effects of patchy ocean fertilization on atmospheric carbon dioxide and biological production, *Global Biogeochemical Cycles*, 17, 1050, doi:10.1029/2002GB001940. See also Sarmiento, J.L., R.D. Slater, J.P. Dunne, A. Gnanadesikan and M.R. Hiscock. 2009. Efficiency of small-scale carbon mitigation by patch iron fertilization, *Biogeosciences Discussions*, 6, 10381-10446.

⁸⁵ Arrigo K.R., R.B. Dunbar, M. Lizotte and D.H. Robinson. 2002. Taxon-specific differences in C/P and N/P drawdown for phytoplankton in the Ross Sea, Antarctica. *Geophys. Res. Lett.* 29, 1938, doi:10.1029/2002GL015277.

⁸⁶ Gnanadesikan, A. and I. Marinov. 2008. Export is not enough: Nutrient cycling and carbon sequestration, *Mar. Ecol. Prog. Series*, 364, 289-294.

the eastern edge of the tropical oceans, can result in organisms using nitrogen rather than oxygen to consume organic matter, a process known as “denitrification.” This process is also an important transient source of the greenhouse gas nitrous oxide. When waters that have lost their nitrogen come to the surface, the carbon in them is released back to the atmosphere. In the recent study by Sarmiento and co-workers, this process substantially reduced the efficiency of patch fertilization at a tropical site.

D. Can oceanic carbon uptake due to iron fertilization be reliably quantified?

In order for any climate change mitigation technology to gain global acceptance, it must be verifiable. This presents particular difficulties for ocean fertilization for three reasons. The first is that carbon does not stay in one place in the ocean, making it impossible to keep track of the carbon resulting from a particular fertilization exercise. The second is that the equilibration of carbon dioxide between the ocean and atmosphere takes many months, making it difficult to monitor the exchange of CO₂ between the atmosphere and the surface ocean. The third is that any verification process must take into account the negative feedbacks outlined in the previous section, and these may be difficult to track and measure. As a result, verification cannot be accomplished by simply measuring carbon fluxes at the fertilization site. A recent model study⁸⁷ demonstrated that much of the uptake from the atmosphere from a localized fertilization takes place over time scales of many months and spatial scales of thousands of km, and amounts to a small change to a poorly known background flux of carbon between ocean and atmosphere. This paper also demonstrated that whether iron fertilization was an effective means of increasing efficiency of the biological pump depended on whether the iron remained associated with other nutrients and accessible to phytoplankton over time scales of decades. Again, verifying such continued association is not currently possible given the poor state of knowledge of the natural iron cycle.

E. Potential negative consequences

An alarming result from Sarmiento and Orr was the finding that fertilization in one region could cause productivity to collapse in another. In their model, fertilizing the Southern Ocean stripped out nutrients from waters that later moved northward, feeding tropical ecosystems. Further research⁸⁸ has suggested that the subpolar region of the Antarctic (north of about 60 degrees) is a region where fertilization would largely shift production from the tropics to the Southern Ocean while removing relatively little carbon from the atmosphere. Working with a more recent model,

⁸⁷ Gnanadesikan, A., J.L. Sarmiento and R.D. Slater. 2003. Effects of patchy ocean fertilization on atmospheric carbon dioxide and biological production, *Global Biogeochemical Cycles*, 17, 1050, doi:10.1029/2002GB001940

⁸⁸ Marinov, I., A. Gnanadesikan, J.R. Toggweiler and J.L. Sarmiento. 2006. The Southern Ocean biogeochemical divide, *Nature*, 441, doi:10.1038/nature04883

Aumont and Bopp⁸⁹ found that Southern Ocean biology could not, in fact, strip out all nutrients from Southern Ocean waters, and they also found that fertilization could reduce ocean productivity in regions at the edges of the subtropics. Moreover they found that if fertilization were turned off, the result would be that global biological productivity became lower than it would have been had no fertilization been applied.

An additional question addressed by model studies is whether iron fertilization might actually exacerbate the greenhouse warming problem. In particular, denitrification, noted above as a negative feedback on the biological pump, also produces the powerful greenhouse gas nitrous oxide. Jin and Gruber⁹⁰ suggested that such nitrous oxide production could offset a significant portion of the extra carbon taken up by the ocean.

Finally, a recent model study has quantified the impact of ocean fertilization on ocean acidification. Ocean fertilization relates to ocean acidification as follows: the goal of ocean fertilization is to cause a phytoplankton bloom in the surface ocean. The growing phytoplankton absorb dissolved carbon dioxide and transform it into organic matter via photosynthesis. This CO₂ absorption temporarily decreases surface ocean acidity, until carbon dioxide from the atmosphere replaces the absorbed gas. Meanwhile, some of the particulate organic carbon from photosynthesis (in the form of algal cells or particles of detritus) settles into deeper water where it is transformed back into CO₂ by the respiratory processes of marine animals and bacteria, thereby increasing the CO₂ concentrations in these deeper waters. Since most of this net release of CO₂ occurs in relatively shallow water directly below the sunlit surface layer,⁹¹ the net result of ocean fertilization is to increase the amount of carbon dioxide, and hence acidity, in the shallow, subsurface ocean. This increased acidity changes the chemistry of ocean water with potential adverse effects on marine organisms, which depend on the existing chemistry for their growth and survival. For example, increased acidification of subsurface waters due to ocean fertilization will decrease the concentration of carbonate ions, which may have negative impacts on numerous marine organisms (such as corals and shellfish) that form their shells and skeletons out of calcium carbonate. The modeling study by Cao and Caldeira⁹² found that massive global-scale ocean fertilization ameliorated surface ocean acidification to a minor degree (about 15% of

⁸⁹ Aumont, O. and L. Bopp. 2006. Globalizing results from in-situ iron fertilization studies, *Global Biogeochemical Cycles*, 20, GB2017, doi:10.1029/2005GB002591

⁹⁰ Jin, X., and N. Gruber. 2003. Offsetting the radiative benefit of ocean iron fertilization by enhancing N₂O emissions, *Geophysical Research Letters*, 30(24), 2249, doi:10.1029/2003GL018458

⁹¹ This is one of the fundamental conclusions from: Lutz, M.J., K. Caldeira, R.B. Dunbar, and M.J. Behrenfeld. 2007. Seasonal rhythms of net primary production and particulate organic carbon flux describe biological pump efficiency in the global ocean. *J. Geophys. Res.*, 112, C10011, doi:10.1029/2006JC003706

⁹² Cao, L., and K. Caldeira. 2010. Can ocean iron fertilization mitigate ocean acidification? *Climatic Change*, doi:10.1007/s10584-010-9799-4.

the total impact needed to balance the increase in ocean acidification caused by increased atmospheric CO₂ under a business-as-usual scenario) but at the cost of moving corrosive deep waters, capable of dissolving the shells of certain marine organisms, hundreds of meters closer to the surface.

IV. International legal framework and applicable law

A. Law of the Sea framework

Customary international law as reflected in the Law of the Sea (LOS) Convention provides the legal framework for all activities conducted at sea, including marine scientific research and ocean fertilization. Under LOS Article 238, “All States, irrespective of their geographical location, and competent international organizations have the right to conduct marine scientific research subject to the rights and duties of other States as provided for in this Convention.” LOS Article 240 lays out the general principles for the conduct of marine scientific research including that “(d) marine scientific research shall be conducted in compliance with all relevant regulations adopted in conformity with this Convention including those for the protection and preservation of the marine environment.”

B. Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention)

In the case of ocean fertilization, the “Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (London Convention)” and the “1996 Protocol to the London Convention 1972 (London Protocol)” have emerged as the principal international regimes for addressing the potential impact of ocean fertilization on the marine environment. Although placing material in the ocean for ocean fertilization would not necessarily be considered ocean dumping, the 1972 London Convention and its 1996 Protocol require that placement of matter for a purpose other than disposal must not be contrary to the aims of the treaties, which focus on the prevention of pollution of the marine environment. Therefore, such placement into the water column should be subject to a system of review and evaluation to ensure the prevention of marine pollution. The United States is a Party to the London Convention (and has signed but not yet ratified the 1996 Protocol), and the domestic law that implements the London Convention in U.S. waters, and for activities taking place on U.S.-flagged vessels or involving material loaded in a U.S. port, is the Marine Protection, Research and Sanctuaries Act (MPRSA). The US Environmental Protection Agency (EPA) is responsible for implementing the MPRSA.

In June 2007, in response to commercial interest in ocean fertilization and the potential of using ocean fertilization to generate carbon credits for sale on the regulated and voluntary emissions markets, the Scientific Groups of the London Convention and London Protocol issued a

“Statement of Concern” on large-scale iron fertilization.⁹³ This was endorsed by the Contracting Parties at their November 2007 meeting and expanded by the Scientific Groups in May 2008, with regard to large-scale and ocean fertilization activities other than just iron fertilization.⁹⁴ In October 2008, the Joint Meetings of Contracting Parties to the London Convention and Protocol adopted Resolution LC-LP.1 (2008) on the Regulation of Ocean Fertilization, which stated that “given the present state of knowledge, ocean fertilization activities other than legitimate scientific research should not be allowed.”⁹⁵ This resolution also stated that scientific research proposals should be assessed on a case-by-case basis using an assessment framework being developed by the London Convention and Protocol Scientific Groups.

As a Party to the London Convention, the U.S. supported Resolution LC-LP.1 (2008), agreeing that any ocean fertilization activity fit the definition of legitimate scientific research, as determined on a case by case basis using the assessment framework that is currently under development by the Scientific Groups of the London Convention and Protocol.

C. Antarctic Treaty System (ATS)

Six of the twelve open ocean iron fertilization experiments took place in the Southern Ocean, and the Southern Ocean remains the primary region of interest for ocean fertilization research. Much of the Southern Ocean falls under the geographical scope of the Antarctic Treaty and other agreements in the ATS, which cover all land and ocean space south of 60° South Latitude. Parties take several actions prior to conducting any activity in the Treaty area, which would include ocean fertilization experiments. The first action involves an environmental assessment process very similar to an Environmental Assessment or Environmental Impact Statement under the National Environmental Policy Act (NEPA). Parties also provide advance notification of the activity to other Treaty parties, and make a commitment to share data with other Treaty parties. Under the Protocol on Environmental Protection to the Antarctic Treaty, parties also have agreed to prevent marine pollution. As a party to the Antarctic Treaty, the U.S. may rely on this Treaty, the Protocol and the U.S. implementation authority to address ocean fertilization activities.

C. Magnuson-Stevens

⁹³ International Maritime Organization, Report Of The 30th Meeting of the Scientific Group of the London Convention and the 1st Meeting of the Scientific Group of the London Protocol, LC/SG 30/14, Sections 2.22-2.28, 25 July 2007

⁹⁴ International Maritime Organization, Report Of The 31st Meeting of the Scientific Group of the London Convention and the 2nd Meeting of the Scientific Group of the London Protocol, LC/SG 31/16, Annex 2, 7 July 2008.

⁹⁵ International Maritime Organization, Report Of The 30th Consultative Meeting and the 3rd Meeting of Contracting Parties, LC 30/16, Annex 6, 9 December 2008

One of NOAA's goals is to advance ecosystem approaches to fishery management. The Magnuson-Stevens Fishery Conservation and Management Act, 16 U.S.C. §§ 1801 et seq., as amended by the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act (MSA) of 2006 (P.L. 109-479), acknowledges that regional fishery management councils have demonstrated significant progress in integrating ecosystem considerations in fisheries management. The Act regulates fishing in the U.S. Exclusive Economic Zone and covers a broad range of activities. For example, it would cover the catching, taking, or harvesting of all forms of marine animal and plant life with certain exceptions. The Act calls for NOAA to maintain a comprehensive program of research to support fishery conservation and management and to include research on, among other things, factors affecting the abundance and availability of fish (Sec. 404). In addition, fishery management plans must contain measures to protect, restore and promote the long-term health and stability of a fishery (Sec. 303). Plans must also describe and identify essential fish habitat (Sec. 303(a)(7)), and federal agencies must consult with NOAA on actions that are proposed, funded, authorized, or undertaken that may adversely affect the habitat (Sec. 305(b)). Ocean fertilization undertaken on a scale necessary to cause a measurable change in atmospheric concentration would likely result in large-scale changes in the structure and functioning of marine ecosystems. Proposed ocean fertilization activities would need to be carefully reviewed to see if they trigger essential fish habitat consultation or other MSA requirements. As noted in previous sections of this report, the science required to perform such a review is far from mature.

V. Conclusion

Fertilizing the ocean with iron (or other nutrients) has been proposed as a mechanism for mitigating climate change, by accelerating the uptake of CO₂ by the ocean. In order for such strategies to work, three criteria must be met: (a) ocean fertilization must lead to increased growth of phytoplankton, packaging carbon and nutrients together into organic material; (b) this organic material must be transferred into the deep ocean so that it does not simply get recycled near the surface releasing its carbon back to the atmosphere; and (c) this transfer of carbon from the surface ocean to the deep ocean must result in a compensating transfer of carbon from the atmosphere into the surface ocean. Research performed by NOAA, its academic partners and the wider research community has shown that while the first part of this chain of events is likely to occur (phytoplankton growth increases following ocean fertilization), the inevitability of the second two criteria is far from certain. Reliably quantifying any net uptake of carbon by the ocean following ocean fertilization is not currently possible, especially in the face of negative feedbacks that would tend to release carbon back to the atmosphere.

Research using ocean models to simulate the effects of ocean fertilization suggests that the maximum impact of ocean fertilization on ocean carbon uptake is likely to be a small fraction of what is required to stabilize atmospheric CO₂ concentrations at twice the preindustrial

concentration. The maximum impact achieved in modeling studies requires continually fertilizing millions of square kilometers of ocean over hundreds of years, a feat that is not technologically feasible.

Ocean fertilization efforts that require manipulating ecosystems at a large scale could also potentially interfere with other legitimate uses of the sea. Potential negative consequences include undesirable changes in the structure and function of marine ecosystems, including ecosystems that support economically important fisheries; reductions in ocean productivity in regions affected by but remote from the fertilization site; increases in mid-ocean and deep ocean oxygen depletion; changes in ocean biogeochemistry that enhance the production of nitrous oxide and methane, greenhouse gases that have a higher heat-trapping potential than CO₂ on a molecule per molecule basis; stimulation of Harmful Algal Bloom forming species, and; net increases in ocean acidification.