Why Ocean Iron Fertilization?

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Overview

The Fourth Assessment Report of Intergovernmental Panel on Climate Change (IPCC) concluded that “It is extremely likely that human activities have exerted a substantial net warming influence on climate since 1750” [Solomon et al., 2007], and that this “is having a discernible effect on physical and biological systems at the global scale” [Rosenzweig et al., 2007]. Starting with the Kyoto Protocol, efforts to mitigate these effects have focused on reducing carbon emissions. Recent international discussions focused on long term targets of about 60-80% reduction in emissions by the year 2050 with the goal of holding the total warming to 2°C above pre-industrial temperatures to “limit the impacts of climate change and the likelihood of massive irreversible disruptions of the global ecosystem” [CEC, 2007]. However, analyses of the proposed emission reduction frameworks suggest that these targets will be insufficient: e.g., “If a 2.0°C warming is to be avoided [by 2100], direct CO\(_2\) capture from the air, together with subsequent sequestration, would eventually have to be introduced in addition to sustained 90% global carbon emissions reductions by 2050”[Weaver et al., 2007]. Furthermore, new observations show that the climate change impacts are already greater than expected and happening more rapidly than predicted [Tin, 2008]. These changes and the potential for abrupt changes due to climate feedbacks suggest that it will be necessary to remove atmospheric CO\(_2\) as well as reduce anthropogenic greenhouse gas (GHG) emissions in order to avoid even more serious impacts.

It is widely accepted that the terrestrial biological carbon sink can be enhanced to reduce atmospheric CO\(_2\) through forestation and agriculture practices. However, the deep ocean is the single largest reservoir of mobile carbon on the planet, and ocean phytoplankton (microscopic algae) are responsible for nearly half the annual CO\(_2\) exchange and a majority of all carbon sequestered over geologic time.

For decades, researchers have studied how the ocean takes up atmospheric CO\(_2\) through the action of phytoplankton that sequester carbon to the deep ocean as they continually bloom, die, and sink (a process called the “biological pump”). A large body of oceanographic research (e.g., [Boyd et al., 2007; Martin and Fitzwater, 1988]) and the geologic record [Winckler et al., 2008] indicate that the availability of iron, a micronutrient essential to photosynthesis in all plants, limits the growth of phytoplankton in large areas of the ocean. Three decades ago, John Martin and Steve Fitzwater proposed the “Iron Hypothesis”, i.e. that the deliberate addition of iron to stimulate phytoplankton growth could mimic the CO\(_2\) reduction during glacial maxima measured in ice core samples [Martin and Fitzwater, 1988]. Since 1993, twelve open ocean experiments have demonstrated that ocean iron fertilization (OIF) is one method of increasing phytoplankton biomass and,

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potentially increasing carbon sequestration. Given the threat posed by rapid climate change and the dominant role of the biologic pump in the Earth’s carbon cycle, it seems important that we determine conclusively whether the purposeful enhancement of oceanic carbon sinks, as well as terrestrial ones, is a possibility that is available to man—and what the impacts of doing so might be. This document discusses the need for expanded research into OIF, highlights the key research questions, and presents some ideas on how this research can be conducted in an effective and environmentally responsible manner.

Why should we complement emissions reductions with CO$_2$ removal?

**Rapid increase in GHG emissions**

Global CO$_2$ emissions have increased faster than the most extreme scenarios developed for IPCC assessments (Figure 1). New data published in 2008 show that GHG emission rates more than tripled between the 1990s and 2007, increasing from 0.9 %/yr to 3.5 %/yr. The response to date has been emission reduction frameworks. However, so far, these have not been effective in reducing atmospheric CO$_2$ levels—in fact, they have failed to even slow the rate of emissions growth. An increase in the energy intensity (GHG emissions/unit of energy) of the global economy, particularly in Asia where there is a heavy reliance on coal power, has been a major factor. Efforts to include developing nations under more stringent caps have been complicated by the inequity implicit when those with the lowest per capita income are asked to cut their already low per capita emissions. Infrastructure transformation has proven to take time, money, innovation and political will—the combination of which has made progress towards emissions reduction targets challenging. More worrisome still, global emissions intensity may increase further if petroleum alternatives (e.g., shale oil, tar sands, and coal-to-liquids) are developed as petroleum reserves peak.

Figure 1: Actual emissions (black lines) now exceed worst case scenario used by the IPCC 4th Assessment Report (red line) - source [Raupach et al., 2007]. Updated with 2005-7 data [http://cdiac.ornl.gov/trends/emis/meth_reg.html].
Decreasing effectiveness of natural carbon sinks

While natural carbon sinks on land and in the ocean have absorbed nearly 50% of all human CO$_2$ emissions, they have declined in effectiveness by 0.25 %/yr over the last 50 years (Figure 2) [Canadell et al., 2007]. For the terrestrial sink this has been attributed to large-scale mid-latitude drought. Recent studies also show that heat stress from anomalously hot years can retard biological productivity for the following two years [Arnone III et al., 2008]. For the ocean, the Southern Ocean natural CO$_2$ sink has weakened by 0.3 GtCO$_2$/yr over the last 23 years due to “the observed increase in Southern Ocean winds resulting from human activities [global climate change], which is projected to continue in the future” [Le Quere et al., 2007]. (1 Gt = 1 billion tons) The reduction in natural sequestration is “consistent with results of climate–carbon cycle models, but the magnitude of the observed signal appears larger than that estimated by models” [Canadell et al., 2007]. The combination of rapidly increasing emissions and decreasing natural sinks “characterize a carbon cycle that is generating stronger-than-expected and sooner-than-expected climate forcing” [Canadell et al., 2007].

Broadening climate change impacts

Many more high quality time series of climate change impacts were available to the IPCC Fourth Assessment Report than to previous assessments. These time series show clear evidence that we are already being impacted by climate change [Parry, 2007]. The report includes evidence of increased runoff and earlier spring peak discharge in many glacier- and snow-fed rivers as well as warming of lakes and rivers in many regions with effects on thermal structure and water quality. A new synthesis of climate models and a 25 year satellite observational record of precipitation found a “distinct link between rainfall extremes and temperature” and that the “observed amplification of rainfall extremes is found to be larger than predicted by models, implying that projections of future changes in rainfall extremes due to anthropogenic global warming may be underestimated.” [Allan and Soden, 2008].

There is also very high confidence that recent warming is affecting terrestrial ecosystems. Spring events, such as budburst, bird migration and egg laying are occurring earlier, while growing seasons are longer for plants. The ranges of plants and animals have shifted both poleward and upward to higher altitudes. The changes in terrestrial ecosystems have begun to negatively affect agriculture, broaden the ranges of vector-borne disease organisms, and increase other factors that affect humans directly. Terrestrial ecosystems are not the only
ones affected by these changes. Warming oceans have caused shifts in the ranges and abundance of marine plants and fish. The times of migration of fish from the ocean to rivers have also changed. At a fundamental ecological level, negative impacts are severe as warming-induced ocean stratification has been linked to diminished biological productivity in the tropical oceans [Polovina et al., 2008] and expanding oxygen-minimum zones [Shafer et al., 2009; Stramma et al., 2008].

In response to the observed difficulty in curbing emissions, Dr. Robert Watson, former Chairman of the IPCC recently stated that, “we should be prepared to adapt to 4°C [temperature rise]” [Randerson, 2008] A 4°C rise would have far-reaching and dramatic negative impacts with increasing drought at mid-latitudes, “significant extinction around the globe”, “widespread coral reef mortality”, and many ecosystems trending toward carbon emission rather sequestration” [Parry, 2007]. The IPCC also notes that continued warming is likely to slow thermohaline circulation in the North Atlantic, which will affect marine ecosystem productivity, oceanic oxygen content, and CO₂ uptake [Schneider et al., 2007].

**Non-linear feedbacks**

Non-linear feedbacks could amplify climate changes being caused by humans. For example, the reduced effectiveness of terrestrial and ocean carbon sinks described above would result in a faster buildup of CO₂ emissions in the atmosphere [Schneider et al., 2007]. However, non-linear feedbacks in polar regions are of the greatest concern. The polar regions are “the regions with the greatest potential to affect global climate”, and which “will produce feedbacks that will have globally significant consequences” [Anisimov, 2007]. Indeed, observed changes in polar environments are happening more quickly than models predict [Stroeve et al., 2007]. In 2007, the summer Arctic sea ice extent was 23% lower than the prior record minimum in 2005 (Figure 3). The 2008 summer sea ice extent was almost as low. When sea ice is absent, the ocean absorbs much more solar radiation and warms more quickly, making it more difficult to freeze during the winter. Further, the thinning sea-ice makes it more susceptible to the effects of wind and other forces, which keep seasonal ice from reforming and thickening as in previous years. The speed at which the extent of summer sea ice is changing is “raising concern that the Arctic may be on the verge of a fundamental transition toward a seasonal ice cover.”[Stroeve et al., 2008].

![Figure 3: Sea ice extent for September 2007, along with sea ice median extent for 1953 – 2000 (red curve), for 1979 – 2000 (orange curve), and for September 2005 (green curve). Inset graph is September ice extent time series for 1953 – 2000. [Stroeve et al., 2008]](image)
A related feedback involves thawing of Arctic permafrost, an “expected” impact of global warming [Anisimov, 2007]. Models suggest that “rapid sea ice loss forces a strong acceleration of Arctic land warming… which can trigger rapid degradation of currently warm permafrost and may increase the vulnerability of colder permafrost for subsequent degradation under continued warming” [Lawrence et al., 2008]. The Arctic permafrost is a large carbon reservoir (one study suggests that it contains roughly 1000 GtC of organic carbon [Zimov et al., 2006]). If it should thaw, GHG emissions could increase dramatically over the next 100 years as the organic carbon decomposes to methane [Zimov et al., 2006]. If all organic carbon in permafrost were released as methane it would be 50 times greater than the historical total of all human GHG emissions (~1800 GtCO₂) [Canadell et al., 2007].

From studies of the past we know that feedbacks have the potential to change climate quickly. For example, it has been suggested that CO₂-circulation-warming feedbacks in the Southern Ocean are the primary mechanism for rapid increase in atmospheric CO₂ at the end of past glacial periods [Sigman et al., 2007; Stott et al., 2007], when at least 1800-5500 GtCO₂ were released from the deep ocean [Adams and Faure, 1998; Sigman and Boyle, 2000]. Greenland ice cores indicate that transformation from the last glacial period to warm conditions in the Northern Hemisphere may have happened in just a few short years [Steffensen et al., 2008], creating a concern that the changes in Arctic sea ice might signal the initiation of these same powerful feedback mechanisms. NASA Scientist Jim Hansen has suggested that the existing CO₂ level of 385 ppm may already have already crossed such a tipping point in the climate system [Hansen et al., 2008].

**Ocean acidification**

One impact of CO₂ is not climate related. Atmospheric CO₂ concentrations have increased so rapidly that we are seeing decreased pH of ocean surface waters [Raven, 2005]. The resulting impacts to ecosystems may be significant, including diminished reproductive success of calcareous organisms [Havenhand et al., 2008] and, potentially, reduced productivity of phytoplankton [Hare et al., 2007]. "Even without global warming, the projected rise in atmospheric CO₂ concentration is hazardous, as ocean acidification will very likely bring about reductions in biodiversity and radically alter ecosystems” [Hall-Spencer et al., 2008].

**Summary**

Although reducing GHG emissions is certainly the first priority to address climate change, the accelerated pace of climate impacts, the potential for non-linear change and the acidification of the oceans argue strongly for further action. Both the IPCC [Metz and Davidson, 2007], and a global supply curve analysis by McKinsey & Company for the Vattenfall Group (Figure 4.) [Vattenfall, 2007] show that the preservation and enhancement of terrestrial sinks is an essential component of overall emission reduction goals (e.g., 60-80% reductions by 2050). We believe that it is important to determine whether the enhancement of ocean sinks should also be a part of the portfolio of climate solutions.
Figure 4: Global Cost Curve for carbon mitigation (abatement). Shows the wide range of technology and practices needed to achieve meaningful carbon sequestration. [McKinsey, 2009]

The Sequestration Power of the Ocean

The ocean carbon reservoir

The deep ocean contains nearly 85% of all of the mobile carbon on the planet (136,000 GtCO₂) –48 times more than the amount of carbon in the atmosphere (2800 GtCO₂) and 12 times more than fossil coal reserves (10,900 GtCO₂) (see Figure 5). The entire anthropogenic CO₂ content of the atmosphere by comparison is only about 750 GtCO₂.

As mentioned above, this deep ocean concentration of carbon is primarily the result of the “biological pump”, a process that begins at the surface where microscopic organisms called phytoplankton use energy from sunlight to convert CO₂ and other nutrients to biomass in events called ‘blooms’ (Figure 6). As a phytoplankton bloom matures over a period of about 60 days, the organisms can be eaten or die. A fraction of the dead phytoplankton, and fecal pellets from the organisms that feed on them, aggregate into falling particles and sink towards the deep ocean. Some of this material decomposes and dissolves back into the water column as it sinks. Carbon that reenters the water column in this way can be trapped in deep water for long periods of hundreds to a thousand years or so. A smaller portion sinks all the way to the ocean bottom and accumulates as sediment, where it can be stored for millions of years or more. The net result is a continual movement, or "pumping", of carbon from the atmosphere into the deep ocean.
Nearby half of the total annual atmospheric carbon turnover is driven by the primary productivity of ocean phytoplankton and about 60 Gt of carbon are moved to the deep ocean each year by the action of the biological pump. This process annually sequesters into deep water about 26% of anthropogenic carbon emissions [Canadell et al., 2007]. Over geologic time, much of the anthropogenic CO$_2$ will eventually be transferred from the atmosphere to the deep ocean by mixing processes and the biological pump, though this transfer will occur over a few thousand years (e.g. [Ridgwell et al., 2007]).

**Impact of changes in the oceanic reservoir with time**

We know that the deep ocean played an important role in the atmospheric CO$_2$ decreases of $\sim$80-100 ppm during glacial times (e.g., [Sigman and Boyle, 2000]) when both the atmosphere and terrestrial biosphere carbon reservoirs were smaller than during non-glacial periods. This suggests that the oceanic carbon reservoir increased during glacial periods [Sigman and Boyle, 2000; Sigman et al., 2007]. However it is very interesting to consider the magnitude of overall carbon exchange, which is much larger than the volume of CO$_2$ removed from the atmosphere alone. During glacial conditions, lower temperatures and reduced precipitation caused desert expansion and the terrestrial biological carbon reservoir was reduced in size by $\sim$5,500 GtCO$_2$ [Adams and Faure, 1998]. The size of this glacial exchange of carbon is roughly eight times the total anthropogenic fraction of CO$_2$ in the atmosphere today, $\sim$800 ppm CO$_2$. The very large size of total CO$_2$ exchange compared to the net atmospheric change ($\sim$100 ppm) strongly suggests that powerful mechanisms drive uptake of CO$_2$ into the ocean.
Figure 6: Biological pump. The deeper the carbon sinks, the longer it will be removed from the atmosphere.

The Southern Ocean and the Biological Pump dominate large scale CO$_2$ changes

Two recent modeling studies suggest that this powerful mechanism of glacial CO$_2$ uptake is the biological pump, which dominated millennial changes of CO$_2$ as part of a feedback cycle concurrent with changes in ocean circulation. Marinov and colleagues [Marinov et al., 2008] compared the relative effectiveness of three
oceanic carbon capture mechanisms, the biological pump, the calcium carbonate pump (CO$_2$ exchange associated with biological formation of calcium carbonate as skeletal material), and the solubility pump (removal of CO$_2$ from the atmosphere by physical solution in surface waters), and found that the biological pump accounted for the majority of atmospheric CO$_2$ a drawdown on millennial time scales. Another modeling study by Schmittner and Galbraith found that increases and decreases in both atmospheric CO$_2$ and N$_2$O on a millennial timescale were dominated by changes to the effectiveness of the biological pump [Schmittner and Galbraith, 2008]. Both studies suggest that the Southern Ocean is the primary region responsible for these large scale changes to atmospheric CO$_2$, and that changes to ocean circulation also play an important role determining the strength of the biological pump.

What is Ocean Iron Fertilization?

In 1988, Martin and Fitzwater showed that an important limit to the growth of phytoplankton in large parts of the open ocean far from land was the iron concentration of the waters [Martin and Fitzwater, 1988]. The principal source of the iron in the open ocean far from land is continental material transported by dust storms [Jickells et al., 2005]. Martin and Fitzwater also recognized that the lowest CO$_2$ levels of glacial maxima corresponded approximately with the highest natural dust flux as recorded in Antarctic ice cores: “We postulate that the enhanced Fe supply from the atmosphere stimulated photosynthesis, which led to the drawdown of atmospheric CO$_2$ levels during glacial maximum.” This became known as the Iron Hypothesis. Martin was also the first to suggest that we could use OIF as a technique to sequester large amounts of carbon from the atmosphere by stimulating the biological pump with iron.

Figure 7: Location of twelve prior iron fertilization experiments (white crosses), natural iron fertilization experiments (red crosses), and excess surface nitrate concentrations (colors on map). Green cross is an iron plus phosphorus experiment [Boyd et al., 2007]
Since the early 1990’s, twelve open ocean experiments have shown that adding iron to iron-limited regions of the ocean triggers large blooms of phytoplankton and that some carbon is sequestered (Figure 7, 8) [Boyd et al., 2007]. These experiments attempted to duplicate the effect of large dust storms that annually deposit tens of millions of tons of iron to the ocean [Jickells et al., 2005] and support primary productivity far from shore. Although the total global amount of iron that is transported to the ocean in dust storms is very large, the amount that is deposited in any region is small, so very small amounts of iron (<5.5x10^{-7} g/l) were needed in the experiments to stimulate large phytoplankton blooms [Coale et al., 1996].

As Martin and Fitzwater noted, the geologic record clearly shows that intervals of increased dust flux have occurred several times in the past million years and for extended periods (thousands of years at a time) and that they are associated with glacial periods of low CO_2. Dust preserved in ice cores worldwide has shown order-of-magnitude increases in iron delivery for sustained periods over the past million years (e.g., [Martinez-Garcia et al., 2009; Petit et al., 1999], Figure 9). Similarly, in ocean sediment records where dust flux and biological productivity have been measured on the same core, the biological productivity of bloom species associated with iron increased during glacial times as dust increased [Winckler et al., 2008]. When lower dust fluxes returned, productivity also returned to interglacial levels.

Recent research on natural phytoplankton blooms, ocean fertilization experiments, as well as the paleoceanographic record strongly suggest the potential of OIF as a carbon mitigation technique. Experiments measuring sequestration from natural phytoplankton blooms show higher carbon sequestration rates than previously thought. The VERTIGO experiment, using the latest sediment trap equipment and
techniques, found that up to 50% of new production of carbon in the North Pacific iron-limited region was sequestered below 500 m [Buesseler et al., 2007]. The KEOPS study in the Southern Ocean iron-limited region measured the highest carbon sequestration rates ever observed from a naturally occurring phytoplankton bloom [Blain et al., 2007]. This bloom was stimulated by the natural mixing of iron- and nutrient-rich sediment from a shallow plateau into surface waters.

The most recent OIF experiment, EIFEX in the Southern Ocean iron-limited region, observed nearly 50% of the bloom biomass (25 T CO₂/km²) being exported below 1000m. This experiment also demonstrated that proper experimental design is important and that experiments that minimize mixing and dilution of the fertilized patch result in high levels of carbon sequestration [Smeteek and Naqvi, 2008].

Figure 9: Ice core record of the last eight hundred thousand years from EPICA dome, Antarctica. Shows temperature (top curve), CO₂ (middle curve), and iron flux (bottom curve). The highest levels of iron (gray vertical bands) correspond to the lowest temperature and CO₂ levels in every glacial cycle. [Martinez-Garcia et al., 2009]
The way forward

In order to understand its potential as a carbon mitigation tool as well as the impacts of deployment at large scale, the international community of scientists in ocean biogeochemistry and carbon cycling have discussed the need for further OIF experiments at patch sizes of up to 200km by 200km. [Buesseler et al., 2008; IOC, 2008; Lampitt et al., 2008]

The consequences of global climate change are profound, and the scientific community has an obligation to assess the ramifications of policy options for reducing greenhouse gas emissions and enhancing CO2 sinks in reservoirs other than the atmosphere. [Buesseler et al., 2008]

The scientific and commercial communities are now ready to collaborate in the pursuit of appropriate field experiments. Given the appropriate financial and legal support, we are optimistic that major advances can and should be made using large-scale field experiments that will address explicitly the effects of various types of ocean fertilization on carbon sequestration. [Lampitt et al., 2008]

Scientists have also identified specific research questions that should be answered to determine the effectiveness of this technique as a carbon mitigation strategy and its potential environmental effects. The following discussion will highlight how future OIF experiments can advance the state of knowledge.

Figure 10: Time evolution of an ocean iron fertilization cruise. Shows that carbon export peaks in the fourth week. Also shows the length of time each prior OIF experiment observed the bloom evolution (top axis) – most stopped observing well before peak carbon export, and thus underestimated carbon sequestration efficiency.
Effectiveness of OIF as a carbon sequestration strategy

First generation OIF experiments were focused primarily on whether iron limited phytoplankton growth, and were not explicitly designed to measure carbon sequestration. Because most experiments were short in duration as well as small and readily diluted by normal ocean mixing, the sequestration potential was almost certainly underestimated (e.g., [Siegel et al., 2008], Figure 10). New, larger experiments will greatly improve the likelihood that measurements of carbon sequestration in the fertilized patch will have far less dilution with water outside the patch and thus increase the accuracy of carbon sequestration measurements.

Because deep ocean circulation is a slow process that occurs on a time scale of hundreds to a thousand years [Matsumoto, 2007], it is the time shifting of carbon into this deep ocean reservoir that contributes to reductions in atmospheric carbon on century to millennial time scales. Two types of evidence can be used to estimate the effectiveness of OIF if deployed at large scales. First, paleo-studies of biologic export and other factors estimate total CO2 drawdown from natural iron fertilization of the Southern Ocean as a result of increased atmospheric dust flux (and hence iron flux). These studies suggest between 37-75 ppm CO2 is removed as a result of naturally occurring ocean iron fertilization [Cassar et al., 2007; Jaccard et al., 2009; Kohfeld et al., 2005; Martinez-Garcia et al., 2009], which is roughly 50-100% of total atmospheric CO2 reductions during glacial times (Bender [2003] explained the non-linear relationship between CO2 and dust resulting from the dust transport distance from land [Bender, 2003].) Second, coupled physical, chemical, and biological models estimate carbon export and atmospheric CO2 removal from various ocean iron fertilization scenarios. These models estimate between 33 – 70 ppm reduction in atmospheric CO2 [Aumont and Bopp, 2006; Brovkin et al., 2007; Gnanadesikan and Marinov, 2008; Marinov et al., 2008]. Two models are particularly relevant to the current CO2 problem as they simulate scenarios in a high CO2 world, and find that a program of globally coordinated artificial OIF has the potential to remove about 33-60 ppm CO2 from the atmosphere over 50-100 years [Aumont and Bopp, 2006; Gnanadesikan and Marinov, 2008]. Table 1 summarizes these results.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Total atmospheric CO2 drawdown (ppm)</th>
<th>Notes</th>
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<tbody>
<tr>
<td>Aumont and Bopp, 2006</td>
<td>33</td>
<td>Model of global artificial OIF over 100 years in high CO2 atmosphere. Explicit iron and biological cycle</td>
</tr>
<tr>
<td>Gnanadesikan and Marinov, 2008</td>
<td>60</td>
<td>Model of global artificial OIF over 50 years in a high CO2 atmosphere. Nutrient restoration technique</td>
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<tr>
<td>Marinov et al., 2008</td>
<td>70</td>
<td>Model of global natural OIF during glacial times. Nutrient restoration technique</td>
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<tr>
<td>Brovkin et al., 2007</td>
<td>37</td>
<td>Model of global natural OIF during glacial times. Nutrient restoration technique</td>
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<td>Cassar et al., 2007</td>
<td>40</td>
<td>Paleo-estimate of Southern Ocean biological pump sequestration during glacial times</td>
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<tr>
<td>Martinez-Garcia et al., 2009</td>
<td>50</td>
<td>Paleo-estimate of Southern Ocean biological pump sequestration during glacial times</td>
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<td>Kohfeld et al., 2005</td>
<td>40</td>
<td>Paleo-estimate of Southern Ocean biological pump sequestration during glacial times</td>
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<td>Jaccard et al., 2009</td>
<td>75</td>
<td>Paleo-estimate of global Ocean biological pump sequestration during glacial times</td>
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Some of the models use a ‘nutrient restoration’ technique as a proxy for explicitly simulating the ecological response to iron addition. This technique assumes that iron addition causes phosphate to become the next limiting nutrient controlling phosphate growth, and therefore total biological carbon export is controlled by the amount of free phosphate in surface waters. This technique does not appear to take into consideration the silica limitation present in the Southern Ocean once iron is no longer limiting, so it may only provide an upper bound on atmospheric CO2 reductions from the Southern Ocean.

![Figure 11: Potential of the biological pump to reduce atmospheric CO2. Assuming a situation in which OIF depletes all excess phosphate nutrients, three scenarios are modeled for large scale OIF (global, Southern Ocean only, and tropical ocean only). This model does not include the effect of silicate limitation in the Southern Ocean, which would likely reduce the potential from what is represented. (graph modified from Gnanadesikan and Marinov, 2008)](graph)

Models require good data to be effective. The moderate-scale field experiments proposed by the science community will provide data that can significantly improve on the ability of ocean models to project the long-term and large scale effectiveness of OIF to sequester significant amounts of atmospheric carbon dioxide.

“There is at present a clear and urgent need for tightly focused research into the effects of ocean fertilisation. The critical areas of research will involve large scale field experiments (100 x 100Km) tightly coupled to high resolution 3D computational models with embedded biogeochemistry” [Lampitt et al., 2008].
Environmental Effects of OIF

In thinking about the environmental effects of OIF, it is important to make a distinction between the currently proposed OIF projects (e.g., 100x100km to 200x200km), which we will refer to as *moderate scale*, and OIF at the scale that would be necessary as a carbon mitigation strategy (*large scale* or ‘*basin scale*’). None of the previous experiments, including the 50 x 50 EiFEX experiment caused any anoxia or harm to ocean ecology. Concerns raised about environmental harm from OIF generally imagine potential harm from large-scale deployment of OIF, not from research experiments. As the Scientific Group of the London Convention (LC-SG) recently noted, even these concerns should be considered “potential” impacts rather than “likely” impacts (see Regulatory Concerns section below) [LC-SG, 2008]. Because we are presently concerned with the research necessary to understand these concerns, we will first discuss potential environmental impacts of the experiments. We will, however, also discuss potential environmental impacts of large scale OIF and how the moderate scale experiments provide information that will allow these impacts to be evaluated.

With careful project design, moderate scale OIF experiments are highly unlikely to have long-term effects on the ocean. The IOC consultative group on OIF observed that if properly designed, moderate scale OIF would be “benign even though conducted over many thousands of square kilometers” [IOC, 2008]. The scientific results from these projects are vital to understand the potential effectiveness and environmental impacts of large scale OIF. For example, moderate scale experiments are necessary to increase our understanding of chemical effects on the ocean environment, including changes in oxygen, nutrient cycles, biogenic gases, etc. They will also be required to look at the impact on phytoplankton assemblages, and other components of the food web [IOC, 2008]. We believe it will be particularly useful for the moderate scale experiments to be conducted as a time series (e.g., 4-5 years of annual projects in one area of the ocean), which would provide additional data on the effects of repeated fertilization that would be necessary in a large scale deployment.

Only with the knowledge from moderate scale experiments can scientists and policy makers understand the potential of large or basin-scale OIF and design large-scale OIF projects that could safely remove large amounts of atmospheric CO$_2$. Improved models will also be crucial for determining the level of large scale OIF that balances the carbon sequestration benefit with acceptable environmental risk.

Ocean acidification

‘Ocean acidification’ is the decrease in surface water pH being caused by rapid dissolution of CO$_2$ from the atmosphere into surface waters [Raven, 2005]. OIF does not contribute to surface ocean acidification because the biological pump removes CO$_2$ from surface waters by photosynthesis (where acidification is a problem for marine organisms that secrete calcareous skeletal material). Thus, there is a temporary increase in pH in the fertilized patch as a result of CO$_2$ drawdown that takes a few months to re-equilibrate with atmospheric CO$_2$ levels. After this time pH levels will be similar to those before the OIF project. We are not proposing that OIF is a strategy to mitigate acidification--the only way to address this problem is to reduce the amount of CO$_2$ in the atmosphere.

If OIF were implemented on a large scale over long time periods, a greater amount of the excess CO$_2$ in surface waters would be transported to the deep ocean. The size of the deep ocean carbon reservoir is three orders of magnitude greater than the total potential annual carbon export from OIF indicated by models [Aumont and Bopp, 2006]. Thus it is still likely that there will be a very small effect on total deep ocean carbon concentration. However, the impact on concentration of the CO$_2$ and carbonate ion components of deep ocean carbon, which control pH and its effects on organisms, will depend on the location and extent of large
scale OIF, and on the depths at which remineralization takes place. A recent simple model of the effect of OIF on ocean pH used a phosphate nutrient-restoration parameterization of carbon export [Cao and Caldeira, Submitted]. This model assumes that OIF would be capable of generating phytoplankton until all phosphate was removed from the surface water everywhere in the ocean. The authors found that surface ocean pH increased slightly while deep ocean pH decreased slightly over 100 years of global OIF. The results significantly overestimate the impact however, because OIF cannot be deployed everywhere and is generally limited by silica long before phosphate is limiting. Determining the impact of large scale OIF on the deepwater CO₂ system should be an objective of further experiments and modeling.

**Oxygen**

Oxygen is consumed by microbial respiration of organic material that is exported to depth via the biological pump. In deepwater open ocean environments, moderate scale OIF experiments would enhance the biological pump and the consumption of oxygen in mid to deep waters. However, the experiments would not result in anoxia and are unlikely to have an impact on oxygen large enough to effect ecosystems for three reasons. First, the effect of OIF is temporary. Every bloom stimulated during OIF experiments that were of long enough duration to see the decline of the bloom -- including experiments that applied iron to the fertilized patch multiple times -- died out after a few weeks and satellite imagines showed that the surface waters returned to their previous low productivity conditions. So increased oxygen utilization would not be ongoing after the cessation of the experiment. Second, the amount of oxygen depletion will also depend on the carbon sequestration efficiency, and the depth distribution of organic material. Estimates of the oxygen drawdown from an experiment with 50% sequestration efficiency are only about 10% greater than unfertilized areas. This decrease is insufficient to create anoxia or excessively low oxygen conditions under the patch [Tetratech, 2009]. Third, experiments of 200 x 200 km are very small in comparison with the amount of ocean mixing that would take place over a season (e.g.[Le Quere et al., 2007]). Thus, even the 10% oxygen depletion will be of limited duration. Modeling can assess the potential for oxygen drawdown during and after specific experiments, and should become part of the Environmental Impact Assessment produced prior to the cruise. The Scientific Group of the London Convention has recommended this as well (in Annex 3 of their report to the full LC/LP meeting in October 2008) [LC-SG, 2008].

The results of the proposed experiments will provide important new constraints on the impact of large scale OIF. While modeling by Sarmiento [Sarmiento et al., 1988; Sarmiento and Orr, 1991] suggested that global-scale OIF would be accompanied by anoxia, the models (which were run before any experiments were conducted) were unrealistic compared to even the most optimistic large-scale fertilization scenarios and entirely unrealistic compared to real bloom processes because they did not include bloom limitation by silica or other factors. In a recent survey of twelve different biogeochemical ocean models, [Najjar et al., 2007] found that ocean circulation plays a much greater role in the oxygen cycle than previously thought, and questioned the assumption of the Sarmiento models that surface phosphate levels are the primary control on deep oxygen levels. They also suggested that more extensive data on the biological pump will improve models of effects from very large scale OIF. Moderate scale OIF experiments would help to provide this data, particularly if conducted as a time-series experiment with fertilization events in the same location over successive years.

**Phytoplankton species changes**

All natural phytoplankton blooms cause changes in the proportion of species because some species are adapted to low-nutrient conditions while others are adapted to high-nutrient conditions. Very small
phytoplankton (picoplankton) generally bloom first, followed by larger phytoplankton, especially diatoms (e.g. [Barber and Hiscock, 2006]). These changes are temporary and the species mix returns to prior conditions after the bloom [Hoffmann et al., 2006]. Lindley and Barber studied the response of photosynthesizers to natural iron stimulation in waters that are "downstream" of the iron-rich Galapagos Islands. They found that the species changes were identical to those of the IronEx II experiment [Lindley and Barber, 1998]. Blain and coauthors also found a succession of photosynthesizers in the Kerguelen Island natural iron enrichment [Blain et al., 2007]. Thus, natural blooms stimulated by increased light or nutrients, natural blooms stimulated by iron, and artificially stimulated blooms all show a succession of phytoplankton, often climaxing with dominance by a group that was rare before the bloom originated. This is natural and not an indication that artificially stimulated blooms change phytoplankton ecology in some new or unexpected way. There is no evidence from the 12 prior experiments of permanent species changes and no reason to believe that moderate scale experiments would be different.

Concerns have been raised that large scale OIF conducted for much longer periods of time might result in permanent changes to phytoplankton assemblages through replacement of one organism or group of organisms by another as a result of repeated fertilization. Studies of present day blooms and paleoceanography both provide evidence about the potential of permanent changes in phytoplankton. The cause of changes in phytoplankton dominance during blooms is an interesting question. There is growing recognition that one assemblage does not replace another, but that the success of the picoplankton and other non-diatom photosynthesizers is controlled by different factors than those that control diatoms. Barber and Hiscock discuss this issue in detail and observe that “…over the years a few very careful observers from Ryther [Ryther, 1969] to Landry [Landry, 2002], who work in oceanic as opposed to coastal habitats, have quietly noted that there is no replacement of the ambient non-diatom assemblage during diatom bloom formation.” (p.2, [Barber and Hiscock, 2006]). Instead, the non-diatom photosynthesizers continue to grow at higher concentrations than under non-bloom conditions, but zooplankton effectively keep them in check. In contrast, diatoms are not effectively grazed by the zooplankton and can continue to grow, using the available nutrients. Thus, there is also no evidence that the climax assemblage of phytoplankton in natural or artificial blooms eliminates or replaces the non-diatom assemblage resulting in some permanent change to the ecosystem. There are still debates in the biological oceanographic community about why the diatoms “overprint” the non-diatoms rather than displace them (e.g. [Morel et al., 1991] vs. [Barber and Hiscock, 2006]), but modern literature agrees that replacement is not happening.

Much of the concern about alteration of plankton assemblages is linked to an assumption that iron might be added continuously in order to keep a bloom going for long periods of time. At larger scales, [Barber and Hiscock, 2006] indicated that fertilization could only be effective once a year. The blooms generally end when diatoms run out of another nutrient, especially silica, or when they become so concentrated that they are self-shaded (this happens in natural blooms as well as fertilized blooms). The phytoplankton assemblages must return to pre-bloom conditions and other nutrients must be restored by mixing before being re-fertilized. However, the issue of phytoplankton species assemblages should be a topic of research during the experiments to determine whether any lasting changes take place after repeated fertilization.

Information about phytoplankton assemblages from glacial ages when dust flux was greater and productivity was higher is limited to phytoplankton that make skeletal material or pigments that can be preserved in sediment. Nonetheless, micropaleontologists find the same organisms preserved in glacial sediments as those of today, but the assemblages have different proportions of species (e.g., [Feldberg and Mix, 2002]). In most regions diatoms are more common during glacial. An important observation is that when interglacial
conditions return the species mix returns to the assemblage of the previous interglacial [Feldberg and Mix, 2002].

It is most likely that fertilization would stimulate those species that are best adapted to take advantage of the additional iron. But there is no evidence that those species would be new organisms or organisms that were not part of the normal phytoplankton population of the region. While we can infer from natural and fertilized phytoplankton blooms that the assemblage will change in proportion, there is no evidence from the past that new species or extinctions resulted from the major changes that occurred between glacial and interglacial. Thus there is little evidence that diminishing biodiversity would be associated with these changes. Furthermore, even when conditions in the past resulted in thousands of years of enhanced iron flux and productivity, there is no evidence that the ocean did not return to its previous non-glacial condition. While it is critical that experiments include study of the results of fertilization and follow the impact of annual fertilization, there is no a priori reason to believe that ocean fertilization will result in changes that are permanent.

**Fisheries**

In thinking about large-scale OIF it is important to note that there is a historic association between greater diatom new production and enhanced fisheries ([Ryther, 1969], [Cushing, 1995], [Smetacek, 1998]). In addition, the melting of icebergs in the Southern Ocean HNLC region creates a natural iron fertilization that supports higher productivity and a diverse trophic community around the icebergs [Smith et al., 2007], as well as higher CO$_2$ sequestration [Raiswell et al., 2008]. Indeed, OIF has been suggested as a mechanism to enhance krill growth and support marine mammal populations [Smetacek and Naqvi, 2008]. Moderate scale experiments would provide an opportunity to evaluate the impact of fertilization on fisheries directly (e.g., do the blooms attract fish?) and indirectly through the food web. The ad hoc IOC consultative group also suggested that moderate scale experiments would be required “to study the impact of [OIF] on the lifecycles of megafauna such as fish” [IOC, 2008].

There have been no observations of fish or megafauna mortality or of other negative impacts associated with previous OIF experiments. In the single experiment that investigated the effect of OIF up the food chain to fish (SEEDS I), the results were positive rather than negative: “Effects of iron enrichment on higher trophic levels, such as fishes, are among the important issues that can be tested only by meso-scale whole ecosystem experiments. Trawl samplings of salmon and other nekton were performed inside and outside of the iron-enriched patch at the end of the experiment (day 14). Although there was no significant difference in salmon catch between inside and outside of the patch, catch of juvenile Northern mackerel was obviously high in the iron-enriched patch.” [Takeda and Tsuda, 2005]. Thus it is unlikely that the moderate-scale experiments would result in harm to fish or megafauna.

**Downstream nutrient changes.** It has been suggested that OIF would use nutrients that would have been biologically productive elsewhere in the ocean resulting in no net increase in productivity and sequestration (so-called “downstream nutrient depletion”). Concern about downstream nutrient depletion is focused on the long-term effect on basin scale fertilization, not the effect of moderate scale experiments. The basis for the concern comes primarily from models [Aumont and Bopp, 2006; Gnanadesikan et al., 2003]. But not all models show nutrient depletion and those that do suggest that the effect is dependent on location of the fertilization. Aumont and Bopp, who used a coupled ecological and biogeochemical model of global scale OIF, found a modest downstream nutrient impact from fertilization conducted in the equatorial Pacific. However, they found no downstream nutrient depletion from OIF conducted in the Southern Ocean because
the short growth season is generally the next limiting factor after iron, not other nutrients, and their model did not simulate the ability of diazotrophic phytoplankton to create nitrites when fertilized by iron. More research is clearly needed to understand whether this potential effect is a problem for downstream regions of ocean productivity.

**Biogenic gases**

While phytoplankton remove CO2 from the atmosphere, they produce other biogenic gases, some of which are radiatively active. There is concern that enhancing phytoplankton productivity might counteract the benefit of CO2 reduction when considered together with the impact of the other gases.

Two potent greenhouse gases, methane and nitrous oxide (N2O) are associated with phytoplankton productivity and remineralization of organic matter, respectively [Fuhrman and Capone, 1991]. Nitrous oxide generation is associated with remineralization at depth under very low oxygen conditions. At the scale of experiments, measurements of N2O production during two ocean fertilization experiments in the Southern Ocean were equivocal. One experiment showed a small amount of N2O generated at depth [Law and Ling, 2001], while the other showed none [Walter et al., 2005]. Even for the experiment that showed evidence of N2O generation, the amount was small compared to the decrease in GHG potential of the CO2 drawdown. These gases should be accounted for in experiments and subtracted from GHG sequestration effects. Measurements of other radiatively active biogenic gases have also been equivocal [Wingenter et al., 2004], with the exception of dimethyl sulfide (DMS), which has increased in all experiments in which it was measured. DMS is associated with increased cloud cover and a cooling effect on the ocean.

At large scales, recent coupled physical/biogeochemical ocean models with a coupled nitrogen cycle have shown substantial N2O generation in some regions (e.g., the tropics), and very little generation in other regions (e.g., North Pacific and Southern Ocean) [Jin and Gruber, 2003]. These results suggest that careful project design could avoid areas of high biogenic gas production. Further experimentation at larger scales could substantially enhance our understanding of the production of these gases, particularly if the equivocal experimental results were related to dilution of the small patches.

**Harmful Algal Blooms**

Harmful algal blooms (HABs) are blooms of algae that produce toxic substances that can affect other organisms. They are predominantly a coastal phenomenon and there is no evidence of such blooms arising from iron fertilization experiments. The algae associated with most coastal HABs are rare in the open ocean and are not associated with natural or iron fertilized blooms there. *Pseudo-nitzschia*, a pennate diatom found in many open ocean regions (e.g.,[Smetacek et al., 2002]), is present in many natural and iron-fertilized blooms, and some, but not all, species of *Pseudo-nitzschia* are capable of producing domoic acid (DA) which is a neurotoxin to some organisms. However, there is an important difference between having the genetic capability of producing DA and doing so. If *Pseudo-nitzschia* species capable of making DA are common in open ocean phytoplankton blooms, do they express this gene and make DA? Wells and coworkers [Wells et al., 2005] are one of the few groups who have studied *Pseudo-nitzschia* in the open ocean. They indicate that DA plays an important role, together with copper, in ensuring that *Pseudo-nitzschia* can survive under very low iron conditions in the open ocean. “This system may explain why *Pseudo-nitzschia* spp. are persistent seed populations in oceanic HNLC regions, as well as in some neritic regions.” (p. 1908). Studies of *Pseudo-nitzschia* strains from coastal waters show that they are more likely to make DA when iron-stressed than when growing under iron-replete
conditions [Maldonado et al., 2002]. Recent studies also suggest that high urea concentrations derived from coastal pollution are necessary to stimulate DA production [Coehlan et al., 2008; Kudela et al., 2008].

Further, and perhaps more importantly, if *Pseudonitzschia* is common in natural blooms in these regions, is there evidence that it is harmful to other organisms? All of the references linking HAB activity from *Pseudonitzschia* and marine mammals or seabirds have been described in coastal waters. There are no references to harmful effects on marine mammals, seabirds or fish from *open ocean* phytoplankton blooms, natural or otherwise, containing *Pseudonitzschia*. There is no a priori evidence of harmful *Pseudonitzschia* blooms associated with OIF experiments, and there is evidence that DA production may be reduced under iron replete conditions. However, study of the potential toxicity of algae associated with OIF should be a high priority for OIF experiments.

**Regulatory Framework for OIF**

A specialized treaty body called the “Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter”, also known as the London Convention of 1972 (LC) and the London Protocol of 1996 (LP), has taken up discussion of a regulatory framework for OIF. This is the primary international regulatory agreement to prevent pollution and harm to the ocean from marine activities associated with ocean dumping and placement of matter into the ocean. There are 88 member countries of the LC (and 35 member countries of the LP). The LC/LP have concluded that review of OIF activities is within the purview of these bodies [LC, 2007]. Other international bodies that have discussed OIF (e.g., the UN Convention on Biological Diversity) have deferred to the LC/LP as the primary regulatory authority with regard to OIF [LC-SG, 2008].

The LC/LP has strong scientific capability through its subsidiary Scientific Groups (LC-SG), and is investigating OIF in detail to determine whether and how ocean fertilization can be conducted in a manner that safeguards the marine environment. The Scientific Groups (LC-SG) have also asked the advice of other UN scientific organizations, including the Intergovernmental Oceanographic Commission (IOC), the Scientific Committee on Oceanic Research (SCOR), and the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP). These groups have supported continued research into OIF to understand the potential for carbon sequestration and the environmental effects of large scale OIF [IOC, 2008; SCOR-GESAMP, 2008]. For example, the ad hoc Consultative Group to the IOC identified that, “Our goal is to safeguard the ocean against damaging ocean fertilization activities without impeding benign fertilization activities; however the scientific community must work to clearly determine what changes are damaging and which are benign” [IOC, 2008].

When the LC/LP parties met in 2007 they endorsed an LC-SG Statement of Concern on Ocean Fertilization [LC, 2007] and gave a directive to the LC-SG to determine whether additional research on OIF was needed, whether larger-scale research was needed, and whether such research would harm the ocean. The final report on ocean fertilization from the May 2008 meeting of the SG-LP states that, because the effects of OIF vary greatly depending on location and scale of the activities:
“...the impacts identified in this advice should be considered as “potential” impacts rather than “likely” impacts. Too much uncertainty remains at this time for the Working Group to ascertain how likely or unlikely such impacts would be.” [LC-SG, 2008]

The implication of this statement is that more research is necessary to understand the effects of large scale OIF. The LC-SG report also proposed a list of considerations on the environmental effects of ocean fertilization proposals, including ecological and biogeochemical effects [LC-SG, 2008]. These considerations are candidates for inclusion in formal Environmental Impact Assessments for proposed projects to determine whether they will be benign in nature.

In October 2008, the LC/LP issued a resolution stating definitively that “the scope of the London Convention and Protocol includes ocean fertilization activities” [LC/LP, 2008]. The resolution also defined “legitimate scientific research” into OIF as “placement of matter for a purpose other than the mere disposal thereof”. This effectively means that scientific research into OIF will not be required to obtain a ‘dumping’ permit from a signatory to the LC/LP, provided that research is determined to be “legitimate”. In this regard, the LC/LP resolution directs the Scientific Group of the London Convention and London Protocol to develop a case-by-case review framework to make this determination for proposed ocean fertilization research projects [LC/LP, 2008].

Other Objections to OIF

In reviewing concerns around OIF we have focused on those raised with respect to its effectiveness and its potential impacts. However, other objections to OIF include philosophic and economic ones as well as the potential for unknown risks.

Unintended consequences and the precautionary principle

Although it is appropriate to question any large-scale environmental manipulation, the results of the twelve previous projects -- as well as what we know about the biological pump -- give us a basis to inform our decisions. However, the potential for unknown risks of OIF has sometimes been used as an argument against further study. Such objections are frequently justified by reference to the “precautionary principle.” This term has many formulations and applications depending on the context. We understand reference to the precautionary principle in the case of OIF to reflect the concept that precautionary measures should be taken when an activity could have the potential for threat of serious or irreversible harm, even where a lack of full scientific certainty about those threats exists. We believe that current efforts to fund and conduct additional experiments in OIF are fully consistent with this approach.

OIF, and even OIF research, are measures undertaken in direct response to the real, and increasing, threat of serious and irreversible environmental damage caused by climate change. One interpretation of the Precautionary Principle is that it is an affirmative duty to take measures -- particularly cost-effective measures -- to mitigate serious, irreparable environmental harms such as those posed by climate change. Viewed in this light, and considering the case we have made for the potential mitigating impact of OIF, research into OIF can be viewed as the essence of precautionary action. We believe that it is fully in line with the exhortation in Rio Principle 15 that, even “[w]here there are threats of serious or irreversible damage, lack of full scientific
certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.” OIF is a technique for environmental mitigation, thus any potential adverse environmental impacts from the technique itself must always be considered in relation to the significant impact on the oceans and other ecosystems arising from anthropogenic climate change.

Moreover, even if we were to apply the precautionary principle as a regulatory tool, and even if we were to consider its application to proposals to conduct additional OIF research in isolation from its role as an environmentally mitigating technology, there is nothing inherent in any standard formulation of the principle that would preclude a properly designed research program on moderate scale OIF. First, it is not clear that OIF research would even trigger a response under the precautionary principle. Most formulations of that principle are concerned with risks of severe harm -- “serious or irreversible damage” in the words of the Rio Declaration. Although some of the potential impacts of basin or global scale OIF that have been hypothesized for OIF are clearly significant, the risks of OIF research are highly unlikely to include such “irreversible” impacts. Not only is the biological activity from phytoplankton normal and widespread, driving approximately 50% of the annual global carbon carbon cycle, but the additional biology created by OIF activities ceases once the supplied iron has been consumed. From that point forward, the system essentially relaxes to its previous lower productivity condition. Any impacts of OIF which are concerns of larger deployments, such as additional oxygen or nutrient demand, would be de minimus in individual projects.

Similarly, the minimum threshold of evidence for potential harm from OIF has arguably not been satisfied in justifying application of the precautionary principle. Most formulations of the precautionary principle serve to lower the threshold of scientific evidence required to show that an activity is harmful in order to justify regulatory controls. The precautionary principle sensibly suggests that full scientific certainty cannot be required before demonstrating that a risk merits regulatory action. But the precautionary principle does not displace the role of science and scientific evidence entirely. The scientific community has indicated that there is insufficient scientific evidence to characterize the risks and potential impacts of OIF activities at this stage as unduly risky. It is similarly insufficient to merely suggest the vague possibility of “unforeseen consequences” as a basis for invoking the precautionary principle, particularly where there is baseline experience with OIF activities from earlier experiments. Instead, further research, including research that involves appropriate monitoring and modeling of long-term impacts, is required precisely in order to help inform future regulatory decisions, including for purposes of application of a precautionary approach.

Second, even if the potential risks from OIF activities were of such concern as to trigger the precautionary response, there is no reason that the appropriate precautionary response would be to prohibit, rather than to regulate or control, OIF activities. We concur with the need to ensure that OIF activities are subject to appropriate oversight and regulatory control, and acknowledge that such regulation is an appropriate exercise of precaution. Indeed, the authors of this paper have participated in, and support, the rule making process under the London Convention.

The precautionary principle does not envision a binary response whereby, if a proposed activity triggers the principle, then it must simply be prohibited. Instead, it is structured as a tool that can be employed by regulators to evaluate the potential risks of an activity even in the face of scientific uncertainty, and it envisions that control measures that are imposed in response should be tailored to address the risks. Rio Principle 15, for example, includes the core idea of “cost-effectiveness.” The 1996 London Protocol includes a general obligation that Parties shall “apply a precautionary approach to environmental protection from dumping of wastes or other matter whereby appropriate preventative measures are taken when there is reason
to believe that wastes or other matter introduced into the marine environment are likely to cause harm even when there is no conclusive evidence to prove a causal relation between inputs and their effects.” Under each of these formulations, the regulatory response that is “appropriate” necessarily depends on the level of knowledge, the scale of the potential risks, and the benefits to be derived from the activity. In the case of OIF, there is no basis for applying these factors in a way that would lead to a prohibition, rather than thoughtful regulation to ensure that OIF activities are conducted responsibly pending the collection of additional data to inform future regulatory decisions.

Indeed, even under the burden-shifting version of the precautionary principle -- which has been called its “most radical” variant [Sand, 2000] -- a phased approach to OIF research is appropriate. Under this version, the proponent of an activity should bear the burden of demonstrating that it is safe before being permitted to proceed. However, the community proposal to build on our knowledge of OIF through a step-wise, carefully controlled set of experiments that are subject to regulatory oversight and designed to evaluate, monitor and model environmental impacts over time, is designed to provide that information. Our group has already initiated an assessment that will assist in identifying environmental impacts and techniques to mitigate them in advance of the commencement of the project [Tetratech, 2009].

OIF as a distraction

Another objection to OIF is that it is a distraction to the hard work of reducing emissions. Sometimes this argument takes the form that our resources and priorities are constrained, and that OIF research is not deserving of them. Other times the argument is that OIF provides an excuse either philosophically, or in the form of a cheap substitute, for those looking for reasons to forestall more serious action. Still others argue that various mechanisms for financing OIF might result in net zero progress towards overall emission reduction targets.

The first argument is a form of prejudice against the effectiveness of OIF as a meaningful carbon mitigation strategy. As we have indicated previously, many scientists are calling for expanded larger-scale, longer duration OIF projects based on the experimental results from the last twenty years. Recent estimates for the long term potential scale and cost of OIF do vary, but generally fall in the range of 1-4 gigatons of CO₂ per year at a cost that is substantially lower than most other approaches (save for energy efficiency which generally has a ‘negative cost’) [Aumont and Bopp, 2006; Buesseler et al., 2008; Gnanadesikan and Marinov, 2008; Jin et al., 2008]. At 1 GtCO₂ per annum, carbon sequestration via OIF would represent a 12% increase in the 2.2 GtC net annual sequestration of the biological pump. At 4 GtCO₂/a, it would imply a nearly 50% increase in net sequestration. It seems clear that OIF is mitigation technique which, if credible, warrants our attention. The only way to understand this potential is to continue to do the research.

The argument that OIF should be discouraged because it could delay direct action on reducing emissions is an argument against any form of response other than emissions reductions. In this line of thinking, even planting a tree for the purpose of climate mitigation becomes a failure of resolve. Yet forestation clearly offers no threat to the primary importance of addressing emissions; we understand that any potential it may have is dwarfed in magnitude by the CO₂ we produce. In the same way, it is clear that OIF cannot ‘fix’ climate change. What is important is that if these techniques can provide a meaningful contribution, that they not be discarded because we lack the resolve to incorporate them into effective policy frameworks.
This argument is also echoed by those that argue against the issuance of carbon credits for OIF because doing so would simply lead to further emissions—and hence no net atmospheric CO\textsubscript{2} reduction benefit [Cao and Caldeira, Submitted]. However, as we have shown in the first part of this article, merely reducing future emissions is not enough to achieve proposed long-term carbon reduction targets (see [Weaver et al., 2007]), or prevent the already substantial observed negative impacts from current CO\textsubscript{2} concentrations, let alone avoid the potential for runaway climate change. More importantly, this argument also ignores the fundamental design elements of current emissions reduction frameworks which oblige emitters to a programmatic schedule of direct emission reductions over time and place strict limits on the total amount of offsets used for compliance.

These frameworks all fundamentally strive to skew the economics of energy towards low or zero carbon sources, enforced through both incentives and as well as strict penalties for non-compliance. Under a ‘cap-and-trade’ system, currently the universally preferred solution, nations and the emitters within them are obligated to emission reduction targets. The ambitiousness of a particular design depends largely on the aggressiveness of targeted reductions over time and the number of industrial and social sectors included under the cap. Offsets, which allow emissions reductions or other carbon mitigation that take place outside the cap (either from uncapped sectors or from outside the geographical area in which emissions reductions are mandated) are included in all current implementations.

The goal of frameworks like cap-and-trade is to force emissions reductions at the most aggressive pace afforded by technology (potential) and economics (pain). The theory of the offset is to enable more potential carbon reductions for the same amount of pain. The use of offsets to fund carbon reductions outside the cap is limited to low percentages (generally 10-15%) in all existing systems—but the decision to allow some offsets reflects a recognition that infrastructure transformation can only occur so fast, and that meaningful carbon reduction opportunities—which can help achieve overall atmospheric CO\textsubscript{2} concentration objectives—can lie elsewhere. Surveys of potential offset supply directly inform decisions about how aggressively to set initial targets, and checkpoints every several years allow new information to calibrate system parameters. Further, the role and limits on offsets in cap-and-trade systems are defined during the initial system design process. It is expected and desired that offset opportunities will be pursued in parallel with direct emission reductions in capped sectors, because together they represent the maximum CO\textsubscript{2} reductions available to society within the time and economic constraints established.

Is OIF a distraction? Only for a society that cannot separate the need to change behavior from other efforts to make progress towards goals. However, the very concept of systems like cap-and-trade is to separate the overall objective of the target (cap) from the various mechanisms to achieve it. This sentiment is clearly and strongly stated in a joint statement by the Academies of Science of the G8+5 countries on a comprehensive approach to both mitigate and adapt to climate change: “There is also an opportunity to promote research on approaches which may contribute towards maintaining a stable climate (including so-called geoengineering technologies and reforestation), which would complement our greenhouse gas reduction strategies” [G8+5, 2008]. OIF can certainly be a part of a portfolio of greenhouse gas reduction strategies without impacting progress toward emissions reductions or a reduction in overall atmospheric CO\textsubscript{2} levels.
Other Response Strategies

The costs, both real and intangible, of adapting to wide-scale climate change will be enormous. The IPCC has noted that we are already adapting to changes in growing season, changes in the patterns of precipitation and other climate impacts. Minimizing the extent of adaptation in the future is an important goal. Short of adaptation, approaches responding to the threat of global climate change fall into four categories: reducing greenhouse gas emissions, avoiding deforestation and other land use contributions to CO$_2$, reducing atmospheric carbon directly, usually by enhancing natural sinks, and limiting the solar radiation absorbed by the earth.

Clearly, our first priority should be to limit emissions. It makes obvious sense to first address the root of the problem. This can be done through conservation, energy efficiency, developing alternative and renewable energy supplies, smart growth planning, sustainable agriculture and development, and possibly CO$_2$ capture and storage (CCS) from a variety of CO$_2$ sources. These strategies vary widely in both readiness and cost of development, with conservation and energy efficiency being the fastest and cheapest. Other technologies, such as CCS will need investment and research now to become feasible in the future. Avoiding deforestation is difficult, but has been prioritized for action in current negotiations. However, emissions reductions alone cannot quickly address both the near tripling of emissions that we are now seeing [Canadell et al., 2007; Vattenfall, 2007] and the accumulated CO$_2$ already in the atmosphere. Some scientists have even suggested that the present level of atmospheric CO$_2$ (~380 ppm CO$_2$) is above a so-called tipping point of irreversible and catastrophic climate change (350 ppm CO$_2$) [Hansen et al., 2008].

We have discussed the use of OIF to enhance the ocean carbon sink, which directly reduces atmospheric CO$_2$ levels. Additionally, a number of techniques have been proposed in recent years to limit solar radiation (also known as Solar Radiation Management (SRM), or albedo modification). These include the injection of stratospheric aerosols to form reflective clouds, “marine cloud seeding” by ships that spray salt water into the air, and orbiting space mirrors to reflect sunlight. These strategies all attempt to limit incoming solar energy before it can be absorbed and trapped and have characteristics that might make them a complement to OIF. By design they do not address CO$_2$ concentration-related problems like ocean acidification. However, in part because they can be deployed and take effect more rapidly, it is possible that the SRM portfolio may include important strategies which could be used in combination with carbon reduction techniques (both emissions reductions and sequestration approaches such as OIF). It is important that these techniques be thoroughly and transparently evaluated by credible scientists in much the same way that we propose for OIF.

Conclusion

The threat of climate change, together with the evidence that its onset is earlier than expected and that its impacts are increasing more quickly than expected, suggests that the pursuit of removing CO$_2$ from the atmosphere will be a necessary risk reduction activity in preventing dangerous effects, including amplifying emission feedbacks. Ocean Iron Fertilization is one such technology with a 20-year history of scientific research that strongly suggests its potential to become a valuable and significant method of atmospheric CO$_2$ removal. The next stage of development for OIF is to conduct a series of new experiments on a moderate scale (e.g., 200x200 km) that are designed to accurately quantify carbon sequestration potential and both immediate and long-term environmental effects. The body of research on OIF suggests that moderate scale experiments can be properly designed to prevent significant environmental harm, and these projects will provide valuable data on the potential carbon sequestration benefit and ecological effects of larger scale OIF. The enhanced scientific knowledge from these projects will allow policy makers to make informed choices.
about the wisdom of implementing large scale OIF in the next decade. Given the rapidity in which both CO₂ emissions are increasing and global warming impacts are occurring, every effort should be made to accelerate the rate of credible scientific research into ocean iron fertilization.

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