

A Response to Concerns about Ocean Iron Fertilization Raised by Greenpeace

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Introduction

Allsopp and co-authors from Greenpeace Research Laboratories recently submitted a Technical Report on ocean iron fertilization (OIF) as a contribution to the 2007 Woods Hole Oceanographic Institution Symposium on Ocean Iron Fertilization (Allsopp et al., 2007). The authors provide a brief review of the development of the OIF concept and the 12 publicly funded experiments that have taken place, followed by a more extensive discussion of “drawbacks” to OIF that they believe argue against any further development of the technique for carbon sequestration. We believe that while Allsopp et al. raise many important issues that need to be discussed, and in some cases addressed by further research, their review 1) does not consider much of the most recent research related to the efficiency of carbon sequestration from natural and stimulated blooms and from models, 2) relies on older, less sophisticated models of OIF than are available now, 3) sometimes extrapolates biogeochemical and ecological data and model results concerning the impact of OIF beyond their appropriate scientific reliability or scalability, and 4) proposes several potential deleterious effects for which there is no evidence in the peer-reviewed literature. Instead, we believe that there are good arguments, supported by the science community, that further experimentation should take place in order to determine whether OIF is an effective carbon mitigation tool and what its impact would be on the ocean environment.

In this technical note we will discuss each of the issues that have been raised by Allsopp and her co-authors in light of the scientific and economic literature and with special reference to the scale at which they might be applicable, including: carbon sequestration efficacy, the physical impacts on ocean and atmospheric chemistry, the effect on marine ecosystems and fisheries, and the appropriateness for commercial participation. This response will address the concerns that have been raised in the sequence that they were discussed by Allsopp et al. [Allsopp, 2007] in order to facilitate following the issues. We also add general sections discussing modeling results and statements of the scientific community with regard to ocean iron fertilization.

The importance of the research background to OIF

In considering the scientific basis for OIF and its impact on the physics, chemistry and biology of the ocean, the discussion must reflect the entire range of techniques that oceanographers have enlisted. The comprehensive research spectrum of OIF has employed theory, process studies, experiments, models, and reference by analogy to similar conditions in the past (paleoceanography). It is also important to differentiate the techniques that have universal applicability from those that apply only in the restricted circumstances in which they were developed. Furthermore, theory has changed considerably in response to real

measurements. For example, theories that the productivity of the ocean was limited by zooplankton grazing have been replaced by a more nuanced understanding of the role of micronutrients like iron [Martin and Fitzwater, 1988] when combined with the limited ability of zooplankton to control larger phytoplankton like diatoms [Landry et al., 2000].

There is a rich literature of process study related to OIF. Small-scale processes are studied with techniques ranging from laboratory studies of pure cultures of specific organisms to shipboard experiments using seawater in bottles with its natural mix of plankton. Larger scale processes require an array of specialties studying the real world over scales of many kilometers and over multiple seasons or years (the Joint Global Ocean Flux Study experiments are the most extensive of these). The purposeful OIF experiments have manipulated one variable (iron concentration in the surface water) and through repetition in several areas, extrapolated results to larger regions of the ocean. Oceanographers have investigated time-dependent processes through time series studies of specific regions and by comparing the present day conditions to periods in the past. These time series records often show changes in some variables that are thought to mimic the changes we see today – especially the transition between glacial and interglacial times when $p\text{CO}_2$ increased by 85 ppm [Petit et al., 1999] and iron from terrestrial dust decreased [Jickells et al., 2005a] [Winckler et al., 2008].

Finally, continued improvements in computing capability over the last decade have allowed increasingly more sophisticated and more inclusive computational models of ocean processes, including OIF. Such models cannot include all processes and variables at small scale, but can be useful if we are mindful of the limitations that the modelers included in order to constrain computation time, of the limitations of knowledge of the specific process being modeled, and of the conditions that were chosen for modeling. It is important to remember that many model runs are never meant to represent reality, but to isolate the impact of a single variable. In this respect they are somewhat analogous to studies of isolates of an individual species of phytoplankton. One can learn about the nature of the organism itself, but not how it interacts in the real ocean.

The importance of assumptions made about how OIF will be deployed

Allsop and her co-authors discuss only the deployment of OIF at a very large scales, using terms like “colossal area that would have to be fertilized” (Exec. Summ.) and frequently refer to “continuous fertilization” (e.g. p. 4). To our knowledge neither ‘colossal’ areas, nor continuous fertilization have been suggested by any commercial entity before a period of experimentation. We also note their citation of references that hold OIF to the standard of its ability to rapidly remove all anthropogenic CO_2 – or a major percentage of it: For example, they refer to Sarmiento and Orr’s modeling study which suggested that the goal of OIF carbon sequestration would be to remove all anthropogenic carbon.

We are not aware of any other carbon emission mitigation strategy or carbon removal strategy that is held to this standard. In fact, most strategies (e.g. forestation, geologic sequestration, large scale deployment of wind turbines) are deemed laudable if individual activities sequester a few tens of thousands of tons of CO_2 or if large-scale deployment of the sequestration or efficiency strategy sequesters or prevents 5 % of emissions (e.g. [Vattenfall, 2007]). We see OIF as one potential tool in the spectrum of activities that we will have to undertake to solve the anthropogenic greenhouse gas problem. Many of the concerns raised by the authors, whether for large-scale experiments or for large-scale commercialization, can be addressed by appropriate choice of fertilization targets and careful project design. As a result the Greenpeace technical note cites many

concerns that do not apply to moderate-scale experimentation (by this we mean fertilization of patches a few hundreds of kilometers on a side) but might need to be considered before more extensive OIF could be deployed.

Many in the scientific community have proposed larger-scale demonstration experiments (at least 100 x 100 km in size) (e.g. [Boyd *et al.*, 2007; Buesseler *et al.*, 2008a]), in order to understand and resolve issues related to the efficacy and the impact of OIF at larger scales. Clearly, members of the scientific community that have expertise in this field of science should carry out such experiments. However, funds for such experiments could come from the private sector as well as from more traditional science-funding sources. Furthermore, we believe that if the scientific community and the carbon market community agree that a verifiable quantity of carbon has been sequestered by such experiments, then the funding entity ought to be able to recover some of the cost of experimentation through the sale of carbon offsets.

There are still many important questions about the potential for OIF as a significant carbon mitigation tool, but given the escalating rate of carbon emissions, the time lags and other challenges associated with technical development of non-carbon or low-carbon technologies, the accelerating impact of greenhouse gas emissions on global climate and ecology, and the impact of CO₂ on ocean pH, it seems vital that we continue to appraise this potential. Previous experiments, modeling, and the opinion of the science community all indicate that experiments at the moderate scales called for do not pose a danger to ocean chemistry or ocean ecology. We will provide substantial peer-reviewed evidence of this point.

It is clear that OIF is not a “silver bullet” to mitigate climate change, and cannot in any way be used to delay actions to reduce GHG emissions. However we strongly believe that it is in the best interest of the world community to support its continued evaluation.

The positions of Greenpeace and Climos

The basic conclusion of Allsopp and her co-authors [Allsopp, 2007], and the inferred Greenpeace position is that:

“From scientific research published to date, it is apparent that iron fertilization would be highly inefficient in terms of carbon sequestration, as well as being highly impractical and costly. Iron fertilization on a commercial scale could be devastating to marine ecosystems including fisheries and, in this regard alone, the risks must be seen as totally unacceptable. Furthermore, commercial iron fertilization could have unpredictable impacts on atmospheric chemistry and global climate through the formation of climate-active gases.” [Allsopp, 2007] (p.14).

We strongly disagree that OIF can be categorically dismissed as “ineffective” and will show that there is substantial published evidence from ocean studies of carbon export, and from natural and artificially fertilized blooms to suggest that OIF could be extremely effective in removing CO₂ from the atmosphere. Published results of recent observations, experiments and models suggest that carbon sequestration by the ‘biological pump’ is more efficient than previously believed. There is also evidence that most chemical impacts can be minimized by appropriate selection of fertilization sites.

While it is true that OIF produces *ecological* changes, as we will show, there is no *a priori* evidence from literature that OIF experiments projects might result in widespread *deleterious ecological* changes. The preponderance of evidence suggests that OIF experimentation and study, even if done at scales of 200 x 200 km, will not harm ecosystems. The detailed effects of more widely deployed OIF on ecosystems cannot be

deduced from the experiments that have taken place to date and therefore cannot be assumed to be negative. However, the response of the ocean to glacial periods of substantially greater dust/iron flux, biological productivity and carbon export argues that it is unlikely that OIF would result in ‘devastating’ effects. We believe that it is prudent to undertake a period of demonstration and experimentation to determine whether this is the case.

We further believe that the private sector can play an important role in this work, as it has in other areas of experimentation and development related to climate change mitigation. We will also discuss issues related to the practicality and cost of OIF, which pose few obstacles, even when using conservative estimates of sequestration and deducting emissions from operations. In order to uphold the highest degree of scientific credibility and ecological protection, we strongly believe that any commercial involvement in OIF must be conducted in close cooperation with the oceanographic and academic communities. We also believe that the regulatory community could endorse specific operational best practices. Climos has proposed elements of a Code of Conduct that might inform such regulations [Climos, 2007].

Carbon Sequestration Efficacy

The first questions about OIF as a CO₂ mitigation technology concern the degree to which it could sequester carbon from the atmosphere: How efficient is the biological pump? Would fertilization sequester a significant amount of CO₂ from the atmosphere? How long could carbon be sequestered? Are other greenhouse gases generated that would offset the CO₂ sequestration?

Why did oceanographers think that the biological pump was extremely inefficient?

The efficiency of the biological pump has been an active area of research for nearly 50 years. It is critical to our understanding of the carbon cycle in the ocean and how that cycle affects climate, the supply of organic material to mid-water and benthic organisms, and more recently, to our ability to quantify and predict the uptake of anthropogenic CO₂ by the ocean. Although a complete discussion of how our view of the biological pump has evolved is inappropriate for this report, it is important to understand why for many years it was assumed that a small fraction of primary productivity was sequestered, as well as the experimental results that have changed this view. Modern attempts to quantify biological carbon export began with Dugdale and Goering’s [Dugdale and Goering, 1967] distinction between “new” primary production and the total primary production. They highlighted the fact that only production supported by the supply of “new” inputs of nutrients was exported and that the remainder was recycled. Eppley and Peterson [Eppley and Peterson, 1979] set the stage for linking new production quantitatively to export by defining the “f-ratio” as ratio of new to total production and showing that it was an asymptotic function of the total production. It was assumed from the beginning that the f-ratio, and therefore the efficiency of the biological pump, could vary. At this early stage biogeochemists (e.g. [Frost, 1984]) proposed foodweb structure as a control on the efficiency of export and there is substantial literature from the late 1980s and 1990s on the relationship between f-ratio and various aspects of the phytoplankton and zooplankton assemblage (e.g. [Elskens et al., 1999]).

A critical set of experiments conducted during the 1980s in the North Pacific that combined sediment trap sampling with other estimates of export [Pace et al., 1987] concluded that roughly 13-25% of the new

production sank beneath the euphotic zone. John Martin and his co-workers summarized all of the sediment trap data from the region [Martin *et al.*, 1987] and suggested that there was little variability across the North Pacific and that approximately 10% of the new production was exported beneath the mixed layer. The conclusions of this summary article were assumed for several years to represent the efficiency of the biological pump, largely because the technology of sediment traps and the interpretation of sediment trap data was contentious and slow to evolve [Gardner, 2000].

What does recent experimentation tell us about the efficiency of the biological pump?

The international Joint Global Ocean Flux Study (JGOFS) was initiated in 1987 to study the processes associated with biological fluxes in the ocean, including carbon export. In a series of comprehensive process studies in all oceans except the Arctic, JGOFS investigators combined study of ^{15}N tracers of new primary production, sediment trap study of particulate organic carbon (POC) flux, study of oxygen and nutrient balances, and a new technique at the time, the flux of the naturally occurring isotope ^{234}Th , which is particle reactive. Each method underwent substantial scrutiny and evolution during the decade of large-scale international process studies in multiple regions of the ocean. Although many questions were resolved, each method still requires careful attention during experiments. Sediment trap experiments, the most direct estimate of the particulate carbon flux, were the subject of very substantial scrutiny (e.g. [Gardner, 2000]).

Before JGOFS, it was thought that there were a few regional relationships that defined the ratio of export to new production. But data from the two JGOFS time-series stations (Bermuda Atlantic Time Series, BATS, and Hawaii Ocean Time Series, HOT) showed that export varied widely with time at the same location – by an order of magnitude at HOT – and that the relationship between primary productivity and export was not constant [Michaels *et al.*, 2001]. These results led to study of other processes that could control export. Many studies emphasized the relationship between diatom blooms and export because 1) the spring phytoplankton bloom in the open ocean generally climaxes with assemblages dominated by diatoms (e.g. [Carlson *et al.*, 1998a] and included references), and 2) diatoms make skeletal material, or ‘tests’, of mineral silica that are heavier than water. The “ballasting” effect that the relatively heavy diatom tests have on sinking POC was studied in several locations (e.g. [Garrison *et al.*, 2000]). Others emphasized the role of mineral particles in ballasting export [Armstrong *et al.*, 2001]. Still others showed that zooplankton fecal pellet production during certain seasons (e.g. [Roman *et al.*, 2000]) or in certain areas (e.g. [Le Borgne and Rodier, 1997]) can substantially increase export rather than just contribute to recycling of organic material. Finally, the diel migration of zooplankton can result in ingestion in surface waters and fecal pellet release at depth, effectively transporting POC directly to deep water [Longhurst, 1991]. These studies as well as others over the last decade began to change the view of an “inefficient” biological pump.

Although these JGOFS studies resulted in substantial insight into the processes that could affect the export of carbon out of the surface waters, they often did not look at the fate of that material beneath the surface mixed layer in which most photosynthesis takes place. A new interest in processes occurring in the “twilight zone”, below the sunlit mixed layer, and how they affect carbon transport to the deeper ocean, resulted in a set of experiments called VERTIGO. VERTIGO used the latest equipment and techniques to look at the fate of carbon below the surface layer. A recent summary of VERTIGO results [Buesseler *et al.*, 2007a], using multiple, replicate deployments to provide error estimates, suggests that export to the deep ocean (below 500 m) can be much greater than the 10% used as a ‘rule of thumb’ for so long [Fig. 1].

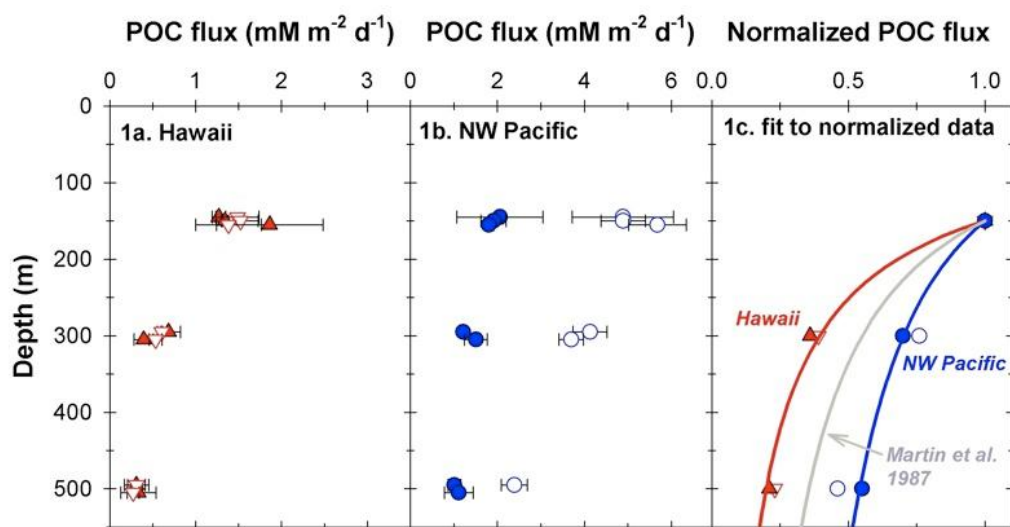


Fig. 1. POC flux versus depth at ALOHA (22° 45' N, 158° W) and K2 (47° N 160° E). (A) POC flux at ALOHA (triangles) and K2 (circles) with open and solid symbols for deployments 1 and 2, respectively. (B) Same data normalized to 150 m POC flux and compared with Martin et al. (4) (dashed line). For each depth, up to three independent neutrally buoyant sediment traps (NBSTs) were deployed from the same launch site, and the POC fluxes are shown (A) for each NBST, with a slight vertical offset, as the mean and standard deviation of replicate POC measurements (n from 2 to 4). Fits to normalized data (B) used a power function of the form $F/F_{150} = (z/150)^{-b}$, where z is the depth of the trap, F_{150} is the POC flux at the 150-m reference depth, and b describes the rate of flux attenuation. [Buesseler et al., 2007a]

In the low productivity central gyre of the Pacific near the “ALOHA” station that is the location of the HOT time series, approximately 20% of the new production that left the mixed layer passed through the 500m depth level. At a moderately productive location in the northwest Pacific (K2, 47° N 160° E, the location of the SEEDS OIF experiments), nearly 50% of the new production was transported to at least 500m [Buesseler et al., 2007a]. Time series measurements at the same location [Honda et al., 2006] show that the VERTIGO experiments took place after the major phase of spring bloom export at K2. These careful experiments are re-shaping thinking about export.

While the recent results of biological pump measurements do not guarantee high efficiency at *all* times and in *all* locations, they clearly indicate that export can be substantial – up to 50% of the new production. None of the many JGOFS studies showing high rates of sequestration were considered in the Greenpeace technical note, nor were the rigorous multi-technique VERTIGO studies although they were published before the Greenpeace report. Further, in several sections the Greenpeace technical note refers to the potential for “reduced oxygen levels in subsurface waters” (p. 3). We will discuss low oxygen and anoxia later in this response, but it is important to point out at this time that it is impossible to generate substantially reduced oxygen or anoxia in deep ocean waters *without* substantial carbon export as the oxygen depletion results from the remineralization of sequestered carbon. If oxygen is reduced in mid- to deep waters after OIF, it is because there has been substantial export. We believe that the results showing substantial export *below the level of deep mixing*, argue that there may be large regions within the world ocean in which substantial POC can be sequestered by OIF.

What can we learn about sequestration efficiency from natural and artificial iron enrichment in the ocean?

Eleven iron-enrichment experiments have been carried out since 1993, two in the equatorial Pacific, two in the northwest Pacific, one in the northeast Pacific, and six in the Southern Ocean. A twelfth experiment in the northeast Atlantic fertilized a patch with phosphate, then with phosphate and iron sulfate. The results of the experiments are covered in an extensive array of published literature – well over 1000 peer reviewed publications – and each of the experiments has been summarized in review articles. In 2007 Boyd and his coauthors [Boyd *et al.*, 2007] summarized the results of all of the experiments in the peer-reviewed literature, as well as three experiments (SAGE, EIFEX and FEEP) that had not yet had summary papers published although results had been presented at international meetings. The Greenpeace technical note provides a brief summary of the results of the experiments as well. Boyd *et al.* (2007) emphasized that the experiments confirm that iron enrichment enhances primary production. There has been little controversy in the literature about the ability of iron to stimulate phytoplankton growth in regions of high nutrient and low chlorophyll (HNLC).

With respect to the amount of that productivity that is exported, the Greenpeace technical note summarizes “Monitoring of export of particulate organic carbon to deeper waters, however, showed that export to deep waters was either very low or could not be detected” (p.8), referring to de Baar *et al.* [de Baar *et al.*, 2005] who said: “in general, the transfer of carbon from dissolved inorganic carbon pools to particulate organic carbon pools via photosynthetic fixation was characterized by large inefficiencies. Only 18-26% of primary production accumulated as particulate organic carbon. Results for export of particulate organic carbon to deeper waters showed that export could not be detected or was very low”. Even setting aside the fact that the efficiencies identified by de Baar, *et al.* [2005] are 2-2.5 x the 10% efficiency that was assumed before the OIF experiments, both the Greenpeace statement and the specific quotations chosen from the de Baar *et al.* (2005) summary simplify a much more complex set of results that we discuss below.

In addition to the artificially fertilized experiments, much can be learned about the potential efficiency of carbon sequestration from the natural iron fertilization that has been studied on the Kerguelen Plateau [Blain *et al.*, 2007a] and the Galapagos Island plume (e.g. [Debernard *et al.*, 1998], [Nomura, 2006]).

Importance of patch size to export

It is important to note that the OIF experiments were designed to determine whether iron limited phytoplankton growth – not the amount of that growth exported to deep water – and that only five of the twelve experiments even included measurements to determine export quantity or efficiency. In addition, all but the EIFEX experiment in the Southern Ocean [Smetacek *et al.*, 2008] fertilized an area about 10 x 10 km in scale. While this area sounds large by terrestrial standards, it is extremely small for the ocean and the fertilized patches underwent so much mixing with waters from outside the patch that it was very difficult for scientists to determine whether they were in or out of the patch when they took their measurements (e.g. [Law *et al.*, 2006]). Sulfur hexafluoride, SF₆, was added to the patches when they were fertilized. SF₆ is not produced naturally in the ocean and the proportion of SF₆ in water samples therefore allowed scientists to determine whether they were in or out of the patch. The SF₆ technique required substantial onboard analysis resulting in adjustments to position before measurements could be made. The scale length of mixing in the ocean. De Baar and his coauthors [de Baar *et al.*, 2005] emphasize that patch dilution at 10 x 10 km was a substantial problem even using SF₆ as a tracer: “In general, the variability and patch dilution interfere with sampling, for example at any given day of any experiment nobody can guarantee the true core (SF₆ maximum) of the patch was sampled.” [de Baar *et al.*, 2005]. Thus, the export measurements represented a very diluted export flux.

(Incidentally, a proven alternative is measurement of quantum yield of fluorescence [Kolber and Falkowski, 1993], which has been shown to be related to nutrient stress [Parkhill *et al.*, 2001] and is also related to iron utilization [Berman-Frank *et al.*, 2001]. Quantum yield can be measured easily while underway and was used successfully by Smetacek during EIFEX to determine when the ship was in or out of the fertilized patch. This new development has obviated the need to use SF₆, a potent greenhouse gas, to trace patches and has essentially automated detection of the blooms either from ship or from autonomous underwater vehicles (AUVs) and gliders (e.g. [Tozzi *et al.*, 2006]).

Siegel and his co-authors on several papers (e.g. [Francois *et al.*, 2002; Siegel and Deuser, 1997; Siegel *et al.*, 2008]) have emphasized that sediment traps and other measurement techniques at depth average flux from a ‘statistical funnel’ that is much larger than the area immediately over the trap. For tethered or untethered neutrally buoyant traps at <500m, traps at a central North Pacific station, ALOHA, collected material from a radius of several 10s of km (Fig. 2, [Siegel *et al.*, 2008]).

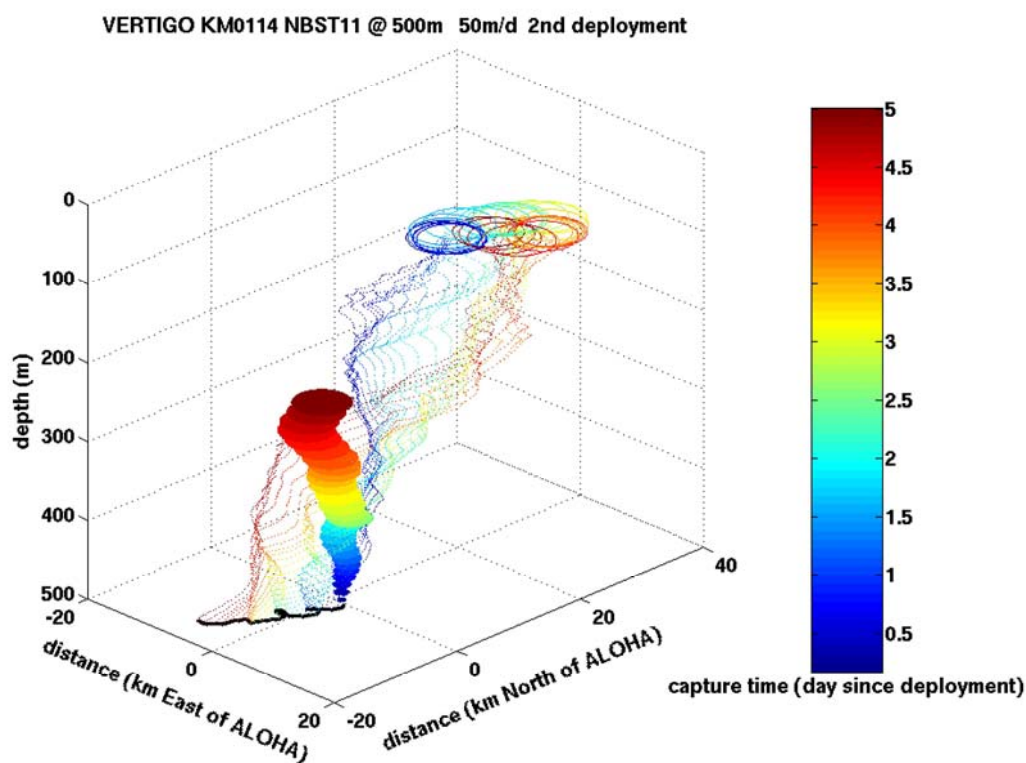


Fig. 2 “Statistical Funnel” for VERTIGO samples at ALOHA station at 500 m [Siegel *et al.*, 2008]. Black line at depth of 500m shows the path of the neutrally buoyant sediment trap away from its point of deployment (at 0,0 on the grid). Colored dotted lines show the path that material arriving at the trap took, depending on the time at which it arrived in the trap relative to the deployment. Note that substantial fractions of the trapped material come from regions in excess of 10 km from the trap.

Observations of trap movement and the size of the area from which material was being trapped for the subtropical Pacific VERTIGO experiment are also applicable to regions like the North Pacific and the Southern Ocean (which have been the site of several OIF experiments), where the surface currents are much

stronger and the circulation is dominated by eddies (e.g. [Talley, 2007]). Particle measurements made in the 10 x 10 km OIF experiments probably incorporated substantial material falling from outside of the patch further diluting the estimates of export. This is one of the several reasons that [Buesseler *et al.*, 2008a] argue that measurements in the experiments cannot be scaled up to represent the results of larger fertilization. The Boyd, et al. summary [Boyd *et al.*, 2007] indicates that they believe that new experimentation is necessary. They also call for experiments in excess of 100 x 100 km.

It is interesting that the largest and longest experiment to date, EIFEX ([Boyd *et al.*, 2007], [Hoffmann *et al.*, 2007], [Smetacek *et al.*, 2007]) in the Atlantic sector of the Southern Ocean, is also the experiment with the greatest evidence of carbon sequestration. Although neutrally buoyant sediment traps and ^{234}Th were not used, the experiment used transmissometry calibrated to water samples from hydrocasts extending from the surface to the seafloor to estimate export. Smetacek and his colleagues observed substantial new productivity ($\sim 44 \text{ g CO}_2/\text{m}^2$), CO_2 drawdown, and estimate the export flux past 1000m at $\sim 36 \text{ g CO}_2/\text{m}^2$.

The natural fertilization that occurs around the Kerguelen Plateau also illustrates the impact of size on export. This large submarine plateau southeast of Kerguelen Island at approximately 50°S 74°E rises to within 500 m of the ocean surface and is several hundred kilometers across. Deep mixing over the plateau suspends iron-containing sediment into the water column and multiple processes result in higher dissolved Fe concentrations over the plateau [Blain *et al.*, 2007a]. pCO_2 measurements in the water column, satellite imagery, and chlorophyll measurements all reflect substantial biological productivity (Fig. 3).

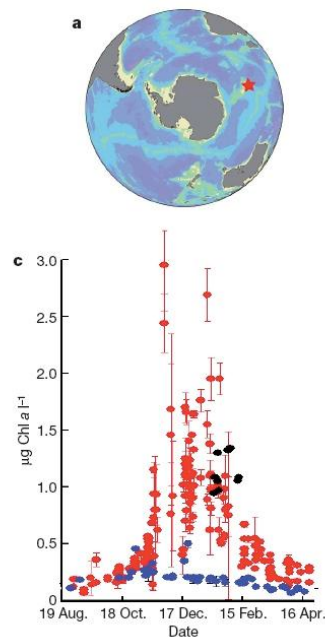


Fig. 3. [Blain *et al.*, 2007a] a, Location of the Kerguelen plateau (red star) in the Southern Ocean. c, Time series of satellite-determined Chl a at stations within the bloom (red dots) and at C11 [outside the bloom] (blue dots). (MODIS results provided by CSIRO Marine Research, Hobart.) Error bars, 61 s.d. calculated from the individual passes of the satellite. Black dots denote high-performance liquid chromatography measurements in surface waters during the cruise.

Note that the Kerguelen bloom lasted for approximately two months. Comparisons of carbon export using the ^{234}Th method showed that export was twice as large in the bloom as out of it, even at 200m depth, and was 10 times as large as the export measured at SoFEX (cf. [Buesseler et al., 2005], [Blain et al., 2007a]). Because the Fe source is from deep water and mixing introduces this iron over the period of the entire bloom the authors are careful to point out that it cannot be assumed that OIF activity would have the same efficiency. Also, the deep water supplying this productivity would have contained a variety of additional nutrients in addition to iron, which likely were a substantial benefit to productivity. Two observations are important: first, it is clear that this is another case of natural productivity than can result in substantially higher export than the 10% levels that have been used in descriptions of the efficiency of the biological pump for many years. Second, the authors believe that the large size of the area fertilized contributed to the high quantity of the export measured [Blain et al., 2007b].

While the Greenpeace technical note states that proposals to consider OIF “*have not taken properly into account the results of the 12 mesoscale iron enrichment scientific studies carried out to date which suggest that the amount of carbon sequestered in this way would be very small...*” (Exec. Summ.), the scientific community has made it clear that the iron enrichment experiments *cannot* be scaled to understand what would happen in a larger experiment:

“A detailed comparison of carbon budgets among the eight Fe experiments would be desirable, but the designs, implementations, weather conditions and actual evolutions of these experiments have been quite different. Patch dilution has notably varied greatly ... and efforts to quantify this using the SF_6 (and ^3He) tracer(s) have proven quite challenging ([Goldson, 2004]; [Bakker et al., 2005]; [Law et al., 2006]), if pursued at all.” [de Baar et al., 2005]

“However, the short observational periods, as well as other intrinsic limits and artefacts of the small scale fertilization technique, have prevented a clear assessment of carbon export and preclude extrapolation to longer timescales.” [Blain et al., 2007a]

“Although these experiments greatly improved our understanding of the role of iron in regulating ocean ecosystems and carbon dynamics, they were not designed to characterize OIF as a carbon mitigation strategy.” [Buesseler et al., 2008a]

In light of this skepticism on the part of the scientific community about the applicability of the mesoscale iron enrichment studies to calculate carbon export efficiency of larger sized patches, we believe that it is not prudent to extrapolate them to larger scale and disagree with Allsopp and her coauthors that the previous experiments can be used as evidence that OIF is not efficient in sequestering carbon.

Importance of experiment duration to export

In addition to the issue of the size of the fertilized patches, several authors have called attention to the short duration of the measurements in contrast to the time over which blooms develop and move into an export phase. A comparison of two fertilization experiments in the Atlantic sector of the Southern Ocean, EisenEX and EIFEX (Fig. 4) shows this very clearly:

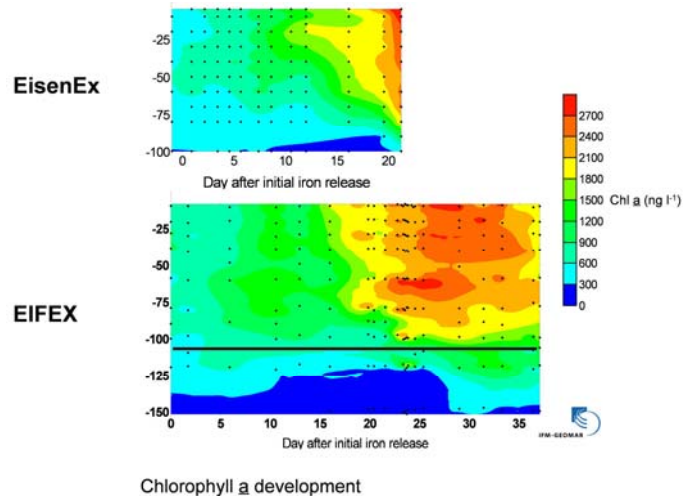


Fig. 4. Temporal evolution of Chlorophyll a in surface water during EisenEX (top panel) and EIFEX (lower panel). Vertical axis is the depth in the water column; the small black dots indicate the depths of samples included in the analysis. They are arranged by the day of measurement after the initial iron release. Both experiments show a similar development of chlorophyll in the bloom and clearly show that the EisenEX bloom experiment ended before the end of the bloom [Smetacek *et al.*, 2007]

Even though the EisenEX bloom was observed for 22 days, it had barely entered the high concentration phase when the experiment ended. Thus, it is unlikely that it would have measured much export compared to EIFEX.

A second example that illustrated the length of time necessary to observe export comes from measurements at the SOFEX sites in the Southern Ocean. A patch north of the Polar Front, SOFEX-N, was fertilized first and an autonomous profiler equipped with a transmissometer was deployed. There were too few ^{234}Th measurements over the course of the experiment to draw conclusions. A more southerly location, SOFEX-S, was studied after the northern patch. ^{234}Th measurements were made over the course of approximately 20d of study. When work was completed at this site the ship returned to recover the autonomous profiler, which had recorded about 60 d of activity in the northern patch (Fig 5). While the SOFEX-S experiment showed inconclusive results, the SOFEX-N transmissometer results show substantial evidence of sequestration [Bishop *et al.*, 2004]. We note that Bishop and others qualify that this bloom may have been subducted under a layer of water, potentially providing an alternate mechanism for the sequestration signal observed.

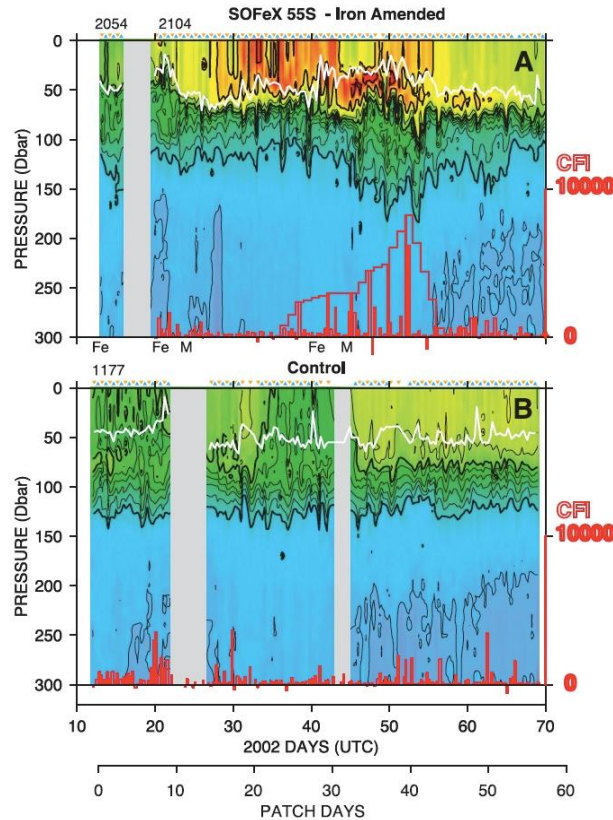


Fig. 5. Time series of transmissometer profiles of particle concentrations with depth (indicated by pressure) of SOFeX-N. Time series of POC variability from (A) Carbon Explorer 2104 (in iron-amended waters) and (B) Explorer 1177 (control) during the first 60 days of deployment. Patch day 0, the start of iron addition, corresponds to UTC day 12.5. The first week of data from Explorer 2054 is included in (A). Cyan up-triangle and orange down-triangle at the top of each panel are plotted at the times of dawn and dusk profiles, respectively. Heavy black contours for cold to warm colors are drawn at 1.0, 2.0, 4.0, and 8.0 μM POC levels. Light contours are at 0.5 μM intervals up to 2.5 μM (except between 1.0 μM and 2.0 μM , where they are drawn at 0.2 μM intervals). Near-surface lows in POC concentration recorded by the “in-patch” Explorer (e.g., UTC days 30 and 34) indicated that it was not always “in” the patch. The white curve is the mixed-layer depth, calculated from the dawn Carbon Explorer profile with potential density data (12). The red line plotted relative to the scale to the right of the figure is the carbon flux index (CFI) (counts d_{-1}) at 100 m. CFI values peaked UTC day 53 (patch day 41). About 150 POC profiles are represented in each of the time series shown. Gray bars are due to loss of profile data caused by transmit buffer overflow on the Explorer as a result of prolonged stormy conditions. CFI data are more frequent because they are transmitted at higher priority. *Revelle* was present at 55°S from 10 to 20 January and for a brief 2-day period in early February 2002. Times of Fe addition by RV *Revelle* are indicated by Fe. RV *Melville* (M) was present for several days during late January 2002 and again briefly in the third week of February 2002. [Bishop *et al.*, 2004]

Several summaries of the previous experiments also highlight the need for longer cruises in order to observe the export phase (e.g. [Buesseler *et al.*, 2008a]). A comparison of the length of time that the OIF experiments were able to stay at their study locations after fertilization in comparison with EIFEX clearly shows that they observed blooms for much less time. If EIFEX is at all typical of open ocean blooms (and a comparison with the Kerguelen natural bloom certainly suggests that it is), then it would have been difficult for any of the other experiments to observe the heavy export phase of the bloom (Table 1):

Experiment	Duration*	Reference	Notes
IronEX I	5	[Martin <i>et al.</i> , 1994]	Bloom subducted after 4 days
IronEx II	17	[Coale <i>et al.</i> , 1996]	
SOIREE	13	[Boyd <i>et al.</i> , 2000]	
EisenEX	21	[Gervais <i>et al.</i> , 2002]	
SEEDS I	10	[Tsuda <i>et al.</i> , 2003]	
SoFEX-S	28	[Coale <i>et al.</i> , 2004]	
SoFEX-N	57	[Coale <i>et al.</i> , 2004]	Bloom subducted. Strong export signal observed. Transmissometers used, patch not continuously monitored.
SERIES	25	[de Baar <i>et al.</i> , 2005]	
EIFEX	37	[Peeken <i>et al.</i> , 2006]	Strong export efficiency observed. Transmissometers used.
SEEDS II	25	[Boyd <i>et al.</i> , 2007]	
SAGE	15	[Boyd <i>et al.</i> , 2007]	
FeeP	7	[Boyd <i>et al.</i> , 2007]	

Role of mesozooplankton grazing to export

Allsopp *et al.* [Allsopp, 2007] raise concerns that mesozooplankton grazing might limit export from OIF. They point out that the OIF experiments were short and that large diatoms bloomed during the studies and escaped predation. They speculate that a longer-term fertilization “*may give larger zooplankton time to increase, though how this would impact on bloom signature is not known*”. They cite Barber and Hiscock [Barber and Hiscock, 2006], who in commenting on episodic fertilization versus continuous fertilization made the statement:

*“Producing a strong export response to iron enrichment requires both initial HNLC conditions and a low background abundance of mesozooplankton, which allows diatom biomass to initially accumulate faster than ambient mesozooplankton can consume it [Landry *et al.*, 2000]. Continuous iron fertilization will not produce efficient sequestration of carbon because as the mesozooplankton become abundant they can continuously graze and recycle a large proportion of the newly produced diatom biomass in the surface layer. This increased grazing rate prevents the accumulation of the diatom biomass needed for efficient export.”*(p. 10)

We think it is important however, to include the very next sentence of the Barber and Hiscock 2006 paper:

“Therefore, efficient engineered carbon sequestration requires episodic Fe enrichment with a return to the ambient picoplankton-dominated assemblage between enrichments.”

Thus Barber and Hiscock were making a point about *which* strategies for OIF *would* be successful, not that OIF would not be successful due to eventual mesozooplankton grazing. Allsopp and her coauthors [Allsopp, 2007] acknowledge this later in their paper saying *“in order to favour carbon sequestration, therefore, it would probably be necessary to repeat iron enrichments periodically, wherein picophytoplankton were again allowed to become dominant between fertilization events”* (p. 9). We see no difficulty with this model of fertilization.

Finally, the continued development of export from the natural iron-stimulated bloom over the Kerguelen Plateau [Blain *et al.*, 2007b] over a period of two months also argues against mesozooplankton grazing limitation of export. Although the Blain paper does not report specifically on diatom concentrations, they have indicated the dominance of diatoms in the later stages of the bloom in presentations. Previous studies of copepod (mesozooplankton) grazing on the Kerguelen Plateau [Razouls *et al.*, 1998] suggest that they consume only about 2% of the plankton biomass during the summer season. Further study of copepod grazing and its impact on Fe recycling also suggests that mesozooplankton consume 1-10% of the total phytoplankton biomass and that abundant diatom populations co-exist with the mesozooplankton [Sarthou *et al.*, 2007].

Our point is not that mesozooplankton grazing pressure could never be an issue, but that nothing that we have found in the published literature demonstrates that it *will definitely* limit the effectiveness of OIF and that larger scale, longer OIF experimentation is necessary to resolve this issue. Therefore it cannot yet be used as a convincing argument against further OIF development.

Non-particulate export

The previous discussion of export has focused on particulate organic carbon (POC) export. However, dissolved organic carbon (DOC) in the ocean is very large, nearly 700 Gt C (an amount equal to all the C in the atmosphere) [Doval and Hansell, 2000]. Oceanographers studying respiration in the ocean calculate that only half of it can be supported by the known particulate organic carbon flux (e.g. [Jahnke, 1996]) implying a large DOC flux as well--and consequently an underestimate of export fluxes calculated only from POC. Di Giorgio and Duarte [del Giorgio and Duarte, 2002a] have suggested that carbon productivity and export estimates to the deep ocean may need to be increased by 50% to account for the respiration that is measured. While DOC flux to the deep ocean is thought to be most important in the low productivity gyres ([Karl *et al.*, 1998], [Lefevre *et al.*, 1996]), there is evidence that it contributes to export in the Southern Ocean as well [Carlson *et al.*, 1998b]. Thus, even the estimates from very careful POC export measurements like VERTIGO [Buesseler *et al.*, 2007a] may substantially underestimate the carbon flux to the deep sea.

Nutrient depletion and export

Allsopp and her coauthors [Allsopp, 2007] raise a complicated issue related to OIF productivity and carbon export -- the potential that OIF-generated export would rob surface waters of nutrients for “normal” productivity: *“A further problem is the depletion of other macronutrients. Iron enrichment drives the consumption of nitrate, phosphate and silica at a rate faster than the ocean can re-supply these macronutrients. Therefore continuous fertilization would not continue to sequester additional carbon because these macro-nutrients would no longer be in sufficient supply and would, themselves, limit production.”* (p.10.) The Greenpeace technical note raises this issue in the context of depleting nutrients in the region of the OIF as well as in “downstream” regions. At this point we will discuss only the

aspects related to limiting the availability of local nutrients and thus affecting export. We will discuss the “downstream” issue under “ecosystem impacts”.

No references are listed for the argument that the natural re-supply rate is too slow to re-supply, but we assume that the basic argument is that once OIF has drawn down macronutrients that the ocean will be depleted and will not be able to support continued export. The statement above uses the term “continuous” fertilization, but does not define what is meant by continuous. Several OIF experiments re-fertilized patches up to four times during a 25-day period. The SOFEX-N patch was refertilized three times. But, as was noted by Allsopp [Allsopp, 2007] in the description of the SOFEX experiment, the experiment did not draw down Si, nor did it consume all N or P [Coale *et al.*, 2004]. Instead the blooms were light limited. EIFEX, the longest of the OIF experiments [Smetacek *et al.*, 2007] also did not consume all of the available N and/or P. These results are typical of OIF experiments. Thus the experimental evidence for multiple fertilization experiments does not support the statement. Continuous fertilization on a scale of weeks has not been shown to result in substantially greater sequestration by several of the OIF experiments [Barber and Hiscock, 2006] and has not been discussed by any commercialization proposals of which we are aware. Instead, single fertilization strategies have been shown to be more effective in sequestration. Upwelling and mixing drive the resupply rate for the local region, which for most regions has a timescale of seasons.

Further, the basic premise of most proposals for OIF is that they would be deployed in HNLC (high nutrient, low chlorophyll) regions that have *excess* nutrients that can *only* be drawn down by additional supply of iron. Thus the addition of the iron is not affecting local productivity that would have taken place in the absence of OIF, it is adding to that productivity.

Insights about export from models

Allsopp and her coauthors [Allsopp, 2007] also refer to model results to discuss both predicted export and atmospheric drawdown from OIF. The primary modeling resource for their discussion is a study using a coupled ocean circulation with biogeochemistry model [Gnanadesikan *et al.*, 2003]. The Greenpeace technical note suggests that “*the efficiency of carbon drawdown from the atmosphere resulting from tropical iron fertilization can therefore be very low, commonly less than 10% over 100 years.*” (p.10) . “*Furthermore, if remineralization occurs near the sea surface, drawdown efficiencies can be as low as 2% of the POC initially exported when extrapolated over 100 years.*” (p.10) [Gnanadesikan *et al.*, 2003]. This study was one of the first to use a fully coupled ocean circulation and biogeochemistry model to simulate OIF and represented an important improvement over simple models used in the past. However, this simulation did not explicitly model the iron cycle, and instead used a “nutrient restoration” approach to mimic the effects of biological iron and nutrient uptake. In addition, the model assumed that biological activity would absorb nutrients and result in carbon export, but did not include an explicit ecological model of plankton dynamics. More recent models from Aumont and Bopp [Aumont and Bopp, 2006] and Jin and his coauthors [Jin *et al.*, 2008] explicitly include the iron cycle in a coupled physical and biogeochemical/ecological model. These models provide a more realistic simulation of the ecological response of the ocean to iron, compared with the simpler model used by Gnanadesikan and his colleagues.

The Gnanadesikan *et al* model [2003] assumed that the ecological response was distributed throughout the entire euphotic zone, which can be very deep in the tropical Pacific (100m) modeled by Gnanadesikan. Jin *et al.* [2008] found that the efficiency of carbon sequestration is very dependent on the vertical distribution of biological productivity. The more realistic biogeochemical/ecological model of Jin *et al.* [2008] showed that the majority of the ecological response to OIF occurs in the upper 10-15m of the ocean. Jin *et al* [2008] argue

that this difference is crucial in determining the carbon sequestration effectiveness of OIF. During a shallow surface bloom, exported particulate organic carbon is replaced by atmospheric CO₂ drawdown, resulting in high atmospheric uptake efficiencies. Jin et al. [2008] also ran scenarios with deep productivity enhancement, and found much lower atmospheric uptake efficiencies in accord with the Gnanadesikan et al. results.

Aumont and Bopp [Aumont and Bopp, 2006] also show that OIF can be an effective means of carbon sequestration. Like the Jin et al. [2008] model, Aumont and Bopp [2006] used a coupled physical and biogeochemical/ecological model, although they simulated fertilization of the entire global ocean for 100 years to simulate the maximum effect of OIF if it were used to mitigate a large fraction of CO₂ in the atmosphere. In a scenario where iron was supplied everywhere in the ocean, Aumont and Bopp found an initial sharp increase in total carbon export from 8.0 GtC/yr in the baseline case to 11.5 GtC/yr in the fertilized case. As surface nutrient supplies became depleted in their model, global carbon export was reduced to 9.8 GtC/yr at the end of 100 years. Again, although we are not proposing widespread deployment of OIF at this time, it is instructive that both models suggest that OIF will result in a substantial increase in carbon sequestration even at very large scales.

The simulations run by Jin et al. [2008] are particularly relevant to the Gnanadesikan simulations for several reasons. First, the simulated spatial and temporal scales were very similar, as each simulated “patch-scale” OIF in the tropical Pacific. Second, Anand Gnanadesikan was a reviewer of the Jin et al. paper (in the *Biogeosciences* journal the reviews and as well as the responses to reviews are available on the website), and his comments and the author’s response are published online. Finally, Jin et al. [2008] explicitly compare the results of their simulations to those of Gnanadesikan et al [2003]. In his review of Jin et al. [2008], Anand Gnanadesikan writes, “*The previous study of patch fertilization discussed here by Gnanadesikan et al. [2003] used two very unrealistic models of production, while this paper uses a realistic prognostic model with an explicit iron cycle.*” This later modeling study was not available to the authors of the Greenpeace technical note since it was published after their document.

Jin and his coauthors [Jin et al., 2008] show atmospheric uptake of 40 tons/km² for fertilization of a 600x600km patch for ten years of continuous fertilization. While we are not proposing immediate transition to widespread deployment of OIF, the Jin et al. model provides some estimates of how effective OIF could be under these conditions. Their work showed 0.34 GtC/yr sequestration for 10-year fertilization of entire North and tropical Pacific. This is not an insignificant number since the total current global ocean net annual sequestration is about 2.2 GtC/yr [Canadell et al., 2007]. Adding in fertilization of the Southern Ocean would likely result in much higher sequestration rates.

The primary results from Jin et al (2008) are: 1) OIF has the potential to be a successful strategy to remove CO₂ from the atmosphere, with higher efficiencies than prior models, and 2) “downstream” depletion of nutrients was not observed. This result calls into question the assertion by Gnanadesikan et al. [2003] that OIF would reduce downstream biologic productivity and therefore reduce carbon sequestration effectiveness as well as generate negative ecological consequences downstream of the fertilized patch. Our point in raising these issues is not that the most recent model is the last word on efficiency of OIF, but that results are model dependent and that they should be used with great caution in developing policy concerning OIF.

Summary

Allsopp and her coauthors [Allsopp, 2007] and others (e.g. Zeebe and Archer [2005]) whom Greenpeace quotes have extrapolated from an early understanding of the efficiency of the biological pump as well as the results of the early OIF experiments to conclude that OIF either cannot work at all or would be so inefficient that it would be inappropriate to deploy. While it may seem natural to extrapolate the relatively modest export measured in the OIF experiments to larger scales and conclude that OIF would not be effective at sequestering carbon, this conclusion is not justified:

- 1) Summaries of the experiments point out that they were too small, were too influenced by dilution, and were measured for too short a time to be models for fertilization at mesoscale (100-200 km on a side), no less for large scale (a few degrees on a side).
- 2) The largest and longest experiment, EIFEX, showed that export took place late enough in the bloom that it was probably missed in shorter experiments – and export in that experiment was substantial (>45% of new production).
- 3) Measurements of natural blooms using state of the art instrumentation show up to 50% sequestration to 500m.
- 4) Natural iron fertilization blooms show >10x the export of small scale experiments.
- 5) Models using full ocean circulation/biogeochemistry/ecology predict substantial export – up to 50% of new production

Geophysical and Geochemical Concerns

Do other greenhouse gases associated with photosynthesis or remineralization offset the carbon sequestered by the biological pump?

Nitrous Oxide

Under certain conditions nitrous oxide, N_2O can be generated by the oxidation of organic material in seawater. N_2O is a greenhouse gas with a greenhouse warming potential about 310 times that of CO_2 [Ramaswamy, 2001]. Thus, a concern is that ocean iron fertilization would generate sufficient N_2O from enhanced organic matter export that it would offset the beneficial carbon sequestration (e.g. [Fuhrman and Capone, 1991]).

When organic material from ocean biological productivity is decomposed by microbial activity (remineralization), much of the nitrogen is oxidized and converted back to soluble nitrogen compounds. During this breakdown of organic nitrogen compounds, N_2O can be generated in two ways. First, in the presence of oxygen, the oxidation of ammonium to nitrate (nitrification) generates a small percentage (about 1 molecule in 1000) of N_2O [Cohen and Gordon, 1979]. Given the approximate ratio of C:N in organic material (about 6.6:1), this would generate about 1 molecule of N_2O for every 6600 molecules of CO_2 and would offset about 4-5% of the CO_2 on a Global Warming Potential basis. This amount should be

accounted for in methodologies for ocean fertilization, but indications are that it would not be significant compared to the likely benefit from CO₂ removal.

When oxygen concentrations are extremely low (<50 mol/kg), a fraction of the organic nitrogen can be converted directly to N₂O [Law and Owens, 1990]. The remineralization of organic material exported to deep water generates oxygen minima at depths of 500-1000 m in most regions of the ocean, but there is still sufficient oxygen that N₂O is not generated in significant quantities. Some regions are characterized by extreme oxygen minima, however. These extreme minima can have multiple origins including consumption of oxygen in place by the respiration of organic material exported from highly productive overlying waters (e.g. [del Giorgio and Duarte, 2002b] and references therein) or advection of low oxygen waters (e.g. [Sonnerup et al., 1999]). If ocean fertilization were carried out in regions with existing very low oxygen concentrations at the depth of organic matter remineralization, or if the fertilization generated enough organic matter to drive oxygen to very low concentrations, much of the CO₂ sequestration benefit could theoretically be offset by N₂O generation. The equatorial Pacific and the tropical Indian Ocean are areas that have extreme oxygen minimum zones. The potential for such an offset has been studied in some of the iron enrichment experiments and has been modeled.

Nitrous oxide concentrations were measured during two Southern Ocean fertilization experiments, SOIREE [Law and Ling, 2001] and EIFEX [Walter et al., 2005] with very different results. During SOIREE Law and Ling [2001] measured the N₂O saturation in surface waters, the air/sea flux, and at depths up to 150m (the pycnocline was at about 70 m). They found no difference between the N₂O saturation and air/sea flux inside and outside the iron fertilized patch. However, measurements of the water column N₂O saturation showed that pycnocline production of N₂O was greater inside the patch than outside the patch. Law and Ling (2001) calculated that the N₂O production they observed would offset no more than 6-12% of the carbon sequestration at the site.

Measurements during EIFEX also showed no difference in the mixed layer N₂O concentration inside and outside of the patch. Unlike during SOIREE, however, there was *no* significant difference between N₂O saturation inside and outside of the patch at depth [Walter et al., 2005]. The EIFEX measurements were made 16 days after iron addition to the patch. The authors speculated that either the SOIREE N₂O generation was a short-term effect or that the very rapid export to depths of thousands of meters during EIFEX was too fast to allow generation of N₂O at mid-depths.

Additional insight into the longer term potential for N₂O production from ocean iron fertilization comes from model experiments [Jin and Gruber, 2003] using a suite of 3-D coupled physical-biogeochemical models [Gnanadesikan et al., 2001], to which the authors added a model of the oceanic N₂O cycle [Suntharalingam and Sarmiento, 2000] and an atmospheric box model to examine the offsetting effects of N₂O. Jin and Gruber [2003] followed both the nitrification pathway and the low oxygen pathway in the model. They considered three different circulation patterns and rates. They also considered ocean iron fertilization of four areas, the North Pacific, the North Atlantic, the tropics, and the Southern Ocean, and used three strategies: 1) continuous fertilization of the entire geographic for 100 years (to simulate a strategy in which significant CO₂ drawdown is the objective), 2) 10 years of fertilization of the entire geographic region (a strategy that has been discussed to “buy time” while policy and technology enable energy economies with lower CO₂ emission rates), and 3) 10 years of fertilization of patches roughly 100 times smaller than the entire region also designed to simulated strategies to “buy time” (see Table 2). Jin and Gruber (2003) indicate that the “low oxygen pathway” is restricted to a few localized regions, such as the tropical Pacific and Indian Oceans.

Table 2. Magnitude of N₂O Offsetting Effect (%) After 100 Years (from Jin and Gruber, 2003)

	100 yr large scale*	10 year large scale	10 year patch**
Tropics	40 (+/-20)	58 (+/-67)	115 (+/-34)
Southern Ocean	13 (+/-6)	11 (+/-18)	-7 (+/-40)
North Atlantic	18 (+/-7)	19 (+/-9)	19 (+/-12)
North Pacific	32 (+/-5)	-5 (+/-31)	-53 (+/-30)

*Tropics (18°S-18°N; 1.20x10¹⁴m²); Southern Ocean (<31°S; 1.06x10¹⁴m²); North Atlantic (31°N-76°N; 0.24x10¹⁴m²); North Pacific (31°N-67°N; 0.24x10¹⁴m²)

**Tropics (116.2°W-105°W; 8.9°S-4.4°N; 0.018x10¹⁴m²); Southern Ocean (150°W-138.8°W; 57.8°W-44.5°S; 0.012x10¹⁴m²); North Atlantic (26.2°W-15°W; 48.9°N-62.2°N; 0.010x10¹⁴m²); North Pacific (168.8°E-180°E; 0.013x10¹⁴m²).

Allsopp [Allsopp, 2007] summarized the results of the Jin and Gruber modeling by saying “Using modeling techniques, Jin and Gruber (2003) predicted that long-term iron fertilization could indeed induce nitrous oxide emissions that would offset the radiative benefits of the carbon dioxide drawdown.” (Allsopp, et al., p.12). While it is true that the model suggests that fertilization could result in N₂O generation, it is also clear from looking at the model data (Table 2) that the amount of N₂O generated depends on the ocean region being fertilized and the length of time over which fertilization is proposed to take place. In some regions there is little enough N₂O generated that it offsets only a small portion of the CO₂ sequestration. Although the Jin and Gruber [2003] model does not generate N₂O in ways that are totally analogous to biological generation in the ocean, the results clearly suggest that activities like the 10-year patch scenarios would not necessarily cause problems. The model suggests that the tropics have the potential to generate sufficient N₂O to offset CO₂ sequestration under almost any scenario, but that the North Pacific and Southern Ocean generate more modest amounts of N₂O that might offset as little as 10% of the CO₂ from 10 yr experiments regardless of scale and as little as 13% of the CO₂ from 100 yr experiments.

The equivocal experiment results from SOIREE and EIFEX certainly indicate that more measurements are necessary to understand the conditions under which N₂O is generated and the conditions under which it might offset significant amounts of CO₂. However, both the experimental and model results also indicate that large N₂O generation would not be an inevitable consequence of ocean iron fertilization if fertilization regions were chosen thoughtfully. The Greenpeace statement that “In the meantime, since it is theoretically possible that nitrous oxide and methane may be produced as a consequence of iron fertilization, and the fact that nitrous oxide has already been detected in one mesoscale iron fertilization experiment, it would be prudent to err on the side of caution by not conducting commercial iron fertilization operations.” (pp. 12-13) ignores a major result of the very modeling study that it quotes – that for large regions and substantial time periods N₂O generation offsets little of the CO₂ sequestered. We

do not believe that a potential CO₂ mitigation option should be ruled out on the basis of only two measurements that are contradictory.

Methane

Methane is a greenhouse gas with roughly 20 times the greenhouse warming potential of CO₂ [Ramaswamy, 2001] that is generally formed by the reduction of organic carbon compounds under anaerobic conditions. Methane is supersaturated in ocean surface waters by 5-75% (e.g., [Scranton and Brewer, 1978]; [Karl and Tilbrook, 1994]; [Tilbrook and Karl, 1995]). The origin of the methane and the mechanism of supersaturation are unknown, as surface waters of the ocean are also saturated to slightly supersaturated in oxygen [e.g. [Talley, 2007]] and should therefore oxidize methane. Researchers have gone so far as to refer to the methane supersaturation as the “oceanic methane paradox” [Kiene, 1991]. Although at least one mechanism has been suggested to explain the supersaturation through the decomposition of methylphosphonate (D. Karl, written communication), there is no agreement on the origin of the methane or on what might control its rate of production.

In spite of the lack of understanding of what generates methane supersaturation, it has been suggested that if the mechanism is related to biological productivity that the methane production could be exacerbated ocean iron fertilization if OIF enhances productivity. Methane production was measured during a few ocean fertilization experiments [Wingenter *et al.*, 2004a]. Lacking a known mechanism, and having few measurements, it is impossible to assess whether excess methane production would result from all OIF activities. Measurements of methane production inside and outside ocean fertilization experiments should be made to understand its relation to OIF.

Potential Deleterious Environmental Impacts

Eutrophication

Eutrophication is excessive primary productivity due to a sustained high supply of nutrients, typically nitrogen and phosphorus compounds. In the coastal ocean, eutrophication results from continuous abundant nitrogen and/or phosphorus from land that sustains high standing stocks of phytoplankton. Subsequent decomposition of the organic material from the phytoplankton leads to low oxygen concentrations or anoxia.

Allsop *et al.*, [2007] have expressed concern that OIF could lead to eutrophication of the ocean, but the open ocean surface waters are much lower in nitrate and phosphate than coastal waters (e.g. [Talley, 2007]) and do not have a continuous surface supply of nitrate and/or phosphate once they have been used by phytoplankton. Instead, these nutrients are supplied from deeper waters by upwelling or during seasonal deep mixing or deep mixing during storms (e.g. [Dugdale and Goering, 1967], [Platt *et al.*, 2003]). Phytoplankton stimulated by OIF use the nutrients and incorporate them into organic compounds, reducing surface waters in the nitrate and phosphate (e.g. about 50% at IronEX II; 75% at SEEDS I; etc.). However, diatoms that also require silica to make their frustules dominate the end stages of most fertilized blooms. In fact, it was silica or light limitation that was the major factor in the decline of these blooms. While some nitrate, phosphate and silica may be rapidly regenerated by decomposition of organic and/or skeletal material in the mixed layer [Dugdale, 1967], a significant proportion is exported to deeper water and is no longer available to support photosynthesis. Phytoplankton blooms generally die out due to lack of one or more of these nutrients together with zooplankton grazing over a period of a few weeks. Every bloom stimulated during OIF experiments that remained at the site long enough to begin to see the declining phases, including

experiments that applied iron to the fertilized patch multiple times, eventually died out and satellite images showed that the surface waters returned to their previous low productivity conditions. Even at Kerguelen Plateau, where substantial iron, together with other nutrients, was being supplied by deep mixing to the sediments on the plateau surface, the bloom eventually died out. Thus the concept of eutrophication, so familiar in the coastal zone, is not applicable in the same way to the open ocean. The supply of macronutrients is not constant. As we have indicated earlier, OIF is more efficient in sequestering carbon when it is carried out episodically, not continuously. For these reasons eutrophication is unlikely.

Anoxia

The cycle of primary productivity in the ocean is tightly coupled to oxygen in both the atmosphere and the ocean. In the deep ocean, two factors control oxygen concentration. First, oxygen is produced as photosynthesis takes place resulting in high oxygen concentrations in surface waters. In regions where surface water sinks to form the bottom waters of the ocean, such as the Southern Ocean and the North Atlantic, the oxygen is carried with the sinking water and ensures that the bottom waters are oxygenated. Second, oxygen is consumed as dead phytoplankton and other organic matter is decomposed by metabolic activity. As organic carbon falls through the water column its decomposition contributes to an oxygen minimum zone that occurs in most ocean regions at roughly 1000m (e.g., [Talley, 2007]).

Allsop et al. [2007] cite a 1991 study [Sarmiento and Orr, 1991] that modeled the effect on OIF on deepwater oxygen concentrations as evidence that, “*iron fertilization would risk dramatic, unpredictable effects on oceanic ecology.*”. While the Sarmiento and Orr work 17 years ago was a pivotal study in the OIF lexicon and has helped to shape scientific investigation of both efficacy and ecological effects of OIF, it was conducted before even the first mesoscale iron fertilization experiment and before the advent of modern coupled ocean/atmosphere models with biogeochemistry and ecological components. Sarmiento and Orr [1991] sought to understand through modeling the maximum CO₂ drawdown that could occur if as much of the macronutrient content of the surface ocean as possible was drawn down by fertilization. They used a simple box model to drive the surface phosphate concentration toward zero over vast reaches of the Southern Ocean, the tropics, the North Pacific, and the North Atlantic for a period of 100 years. All surface phosphorus was assumed to be taken up by organic material in the Redfield Ratio (106 C: 16 N: 1 P) during the entire year. The model then simulated export of all organic material directly to the deep ocean and respiration was allowed to decompose the organic material. In this rudimentary model of the ocean -- that did not include atmospheric and ocean circulation, not to speak of biogeochemical recycling -- fertilization of the Southern Ocean was seen be most effective in reducing CO₂. The model indicated that anoxic conditions in the bottom waters would be generated under these unrealistic conditions.

As Allsop et al correctly identified, the Sarmiento and Orr simulation used an extreme scenario of total phosphorus depletion. This would not be a realistic assumption if even a sustained program of OIF were conducted on a large scale because OIF blooms (most of which terminated with diatoms as the dominant phytoplankton) are generally limited by Si or light, not P (e.g. [de Baar et al., 2005]). While this model was useful to call attention to the relationship between deepwater oxygen consumption by respiration and OIF, it was, and still is, wholly unrealistic for OIF for many reasons. First, it assumes that you *could* draw phosphorus down to zero concentration over extended periods by OIF. This has not happened in the OIF experiments – even those with multiple iron doses. The model also draws phosphorus to zero in regions of the ocean that are not limited by iron and would be unlikely targets for OIF, including much of the Atlantic. Finally, the model includes no physical or biological regeneration of nutrients and organic material in the surface waters.

In the past seventeen years, experimental results and more realistic models have produced significant advances that call the results of this simple model into question. We do not believe that it should be used to formulate OIF policy.

Do we know how OIF would affect deep ocean oxygen levels? Certainly an increase in OIF-driven carbon export would consume oxygen in midwaters, however modeling the relative impact of this increase in consumption is complicated by the dual roles of carbon export and ocean circulation. Deepwater oxygen levels are a balance between consumption of oxygen by organic material that has fallen into deep water and “ventilation” of the deep ocean by high oxygen surface water. The most recent, and most complete, evaluation of model results for oxygen in deepwater was an analysis of 12 global ocean circulation models by Najjar et al. [Najjar et al., 2007], who examined the effects of carbon export on deep oxygen content. The purpose of their analysis was to test existing models' capability to reproduce the observational record of carbon export, dissolved organic carbon, dissolved oxygen, and circulation tracers such as ^{14}C . All of the circulation models were coupled to a common biogeochemical model, and used a phosphate nutrient restoration approach to simulate primary productivity, but none of the models included ecology (i.e. they did not mimic the succession of biological activity associated with a bloom). Najjar et al. [2007] found that deep ocean oxygen concentration was strongly correlated with ocean circulation and carbon export, as one would expect, however all but two of the models reproduced consistently lower deep oxygen levels than observational records. There was also a wide variation, the “mean AOU [apparent oxygen utilization] for waters deeper than 2 km varies by more than a factor of two among the models” [Najjar et al., 2007]. The cause of the poor deep oxygen simulation was assumed by the authors to be related to problems in modeling the circulation of oxygen, and not due to variations in carbon export among the models. The authors however recognize that the observational records of carbon export are limited: “To be conclusive, however, more sediment trap observations are needed, as most of the long-term deployments have been in the Northern Hemisphere [Francois et al., 2002]”. They also argue that the models need to be constrained by other types of observations: “Overall, the results emphasize the importance of physical processes in marine biogeochemical modeling and suggest that the development of circulation models can be accelerated by evaluating them with marine biogeochemical metrics.”. Our point is that even the best models have difficulty simulating the real world and the modelers highlight the need for experimentation to constrain the models.

Najjar et al. (2007) concluded that the ability of models to predict deep ocean oxygen profiles is currently limited. Furthermore, their research suggested that ocean circulation plays a much greater role than previously thought, and they questioned assumptions of prior models by Sarmiento [Sarmiento et al., 1988; Sarmiento and Orr, 1991] that surface phosphate levels provide a primary control on deep oxygen levels: “The large range of deep-ocean AOU is surprising in light of box model studies [e.g. Sarmiento et al, 1988] that suggest that oxygen content of the deep ocean is regulated by the concentration of surface phosphate in regions of deep water formation... regardless of the rate of ocean circulation and export production.” Najjar and his coauthors [2007] suggest that models of deep ocean oxygen could be improved through better physics of atmosphere-ocean exchange of O_2 for newly ventilated waters, and through improvements in the high latitude observational record for both carbon export and for surface phosphate levels throughout an entire year.

Allsopp et al. [2007] cite Bakker [Bakker, 2004] who concluded that “It is possible that commercial long-term or large-scale fertilization programmes could create conditions with “zero oxygen concentrations” (anoxic conditions) at intermediate depths. Low oxygen levels and anoxic conditions would have a negative impact on all aerobic marine organisms.” (p.12) However, in 2004 Bakker had only the Sarmiento and Orr [1991] paper as a guide in the absence of later modeling that suggests that the assumptions of the Sarmiento and Orr work are incorrect.

Given the current difficulties of models to accurately reproduce deep ocean oxygen levels, OIF policy should not be based on predictions of deep ocean anoxia from older models [Sarmiento and Orr, 1991]. Rather, improving the performance of newer models should be carried out through further observations of natural ocean blooms as well as the assimilation of the data from further OIF experiments, particularly in the Southern Ocean. Such activity would develop a more complete observational record required for tuning the models, and in particular satisfy the “need for greater spatial coverage and for methods to extrapolate measurements to basin-wide scales with error estimates” [Najjar and al, 2007].

Harmful Algal Blooms (HABs)

Species capable of producing toxins occur in small concentrations in most of the ocean. We are very concerned about them when blooms in coastal waters and enclosed seas like the Baltic contain significant concentrations of toxin-producing algae. Under these circumstances the toxins can be concentrated by the action of shellfish filtering waters and, in some circumstances, can affect fish and/or produce aerosols that can be harmful to humans. There is abundant evidence in the literature of the impact of toxins from harmful algal blooms (HABs) on human health, the health of marine mammals and birds, on fish, and even on the zooplankton that feed on toxin-secreting algae (e.g. [Smayda, 1997b]).

The Greenpeace technical note raises the potential that fertilization may result in harmful algal blooms (HABs) and concludes: *“In the light of the risk of harmful algal blooms occurring as one consequence of an increased supply of iron, it would be prudent not to carry out large-scale iron fertilization as a carbon sequestration strategy”* (p.12).

The natural phytoplankton blooms that form the base of the food chain are diverse and vary from region to region. For example, natural blooms along the equatorial Pacific upwelling area commonly contain more than 200 taxa including diatoms, coccolithophorids and dinoflagellates (e.g., [Chavez et al., 1990]; [Kaczmarek and Fryxell, 1995]) of which about 15-20 will be common. These natural blooms in the open ocean (and OIF stimulated blooms) generally have a succession of dominant forms ending with diatoms. But Smayda [Smayda, 1997a] cautions against making inferences about the dynamics of open ocean diatom-dominated blooms from coastal blooms, especially harmful algal blooms (HABs), and vice versa. He points out several important ways in which they differ. For example, most coastal and enclosed-sea HABs are dominated by flagellates (Smayda, 1977), many of which rely on resting stages that remain in sediments and are resuspended during strong mixing events. The great depth of the open ocean precludes re-inoculation of waters from the sediments.

Therefore, in looking at the potential for toxic blooms in association with ocean iron fertilization several questions are important:

- Are phytoplankton species that are capable of producing toxins generated under normal open ocean bloom conditions?
- Does ocean iron fertilization stimulate similar species or toxin-producing species that do not occur in natural blooms?
- Are such species produced in sufficient quantities during fertilization to be a hazard to marine life typical of these areas?
- How do other elements of the food chain respond to toxin-producers in natural blooms?

In the equatorial Pacific upwelling area there is little difference in the bloom assemblages between the low productivity El Niño conditions and normal high-productivity non-El Niño years (e.g., [Iriarte and Fryxell, 1995]) with the exception of species of *Pseudonitzschia*, a pennate diatom that is virtually absent in lower productivity conditions [Kaczmarek and Fryxell, 1995]. *Pseudonitzschia* is also one of the species that may occur in blooms in temperate regions like the northwest Pacific and during high productivity periods along the Antarctic front [Smetacek et al., 2002]. Some, but not all, species of *Pseudonitzschia* are capable of producing domoic acid (DA), a neurotoxin. So this genus capable of producing DA is present in natural open ocean blooms. But there is an important difference between having the genetic capability of producing DA and doing so.

If phytoplankton capable of making DA are common in open ocean phytoplankton blooms, do they express this gene and make DA? There have been few measurements published related to the *expression* of the gene for DA in open ocean phytoplankton. Wells and coworkers [Wells et al., 2005] are one of the few groups who have studied *Pseudonitzschia* in the open ocean. They indicate that DA plays an important role, together with copper, in ensuring that *Pseudonitzschia* can survive under very low iron conditions in the open ocean. “*This system may explain why Pseudonitzschia spp. are persistent seed populations in oceanic HNLC regions, as well as in some neritic regions. Our findings also indicate that in the absence of an adequate copper supply, iron-limited natural Pseudonitzschia populations will become increasingly toxic.*” (p. 1998). We know from studies of *Pseudonitzschia* strains from coastal waters that they are more likely to make DA when iron-stressed than when growing under iron-replete conditions: “*Our findings suggest that DA production during exponential growth of these two toxigenic Pseudonitzschia species is directly induced by Fe-deficient or Cu stress conditions and that 95% of this DA is actively released into the medium.*” (p. 515) [Maldonado et al., 2002].

Because of this adaptation that gives *Pseudonitzschia* spp. a survival advantage under low iron conditions, they are a common component in the artificially fertilized OIF blooms as well as natural blooms: IronEx I and II [Cavender-Bares et al., 1999], SERIES [Denman et al., 2006], SOFEX, EisenEX, (and a minor component of the diatom bloom during SEEDS I that was replaced by a centric diatom [Saito et al., 2005]). To our knowledge there have been no studies during the fertilization experiments to determine whether *Pseudonitzschia* was generating domoic acid during the fertilization. And there have been no observations of harmful effects on marine mammals or seabirds during these experiments.

Given that *Pseudonitzschia* is present in both the natural and fertilized blooms in these regions, is there evidence that it is harmful to other organisms? *Pseudonitzschia* diatoms are also present in coastal areas and have been associated with some HABs in these regions that have affected marine mammals and seabirds [Schnetzler et al., 2007]. In fact, all of the references linking HAB activity and marine mammals or seabirds have been in coastal waters. We are not aware of any reference to harmful effects on marine mammals, seabirds or fish from *open ocean* phytoplankton blooms, natural or otherwise, containing *Pseudonitzschia*. Indeed, it would seem unusual to have *Pseudonitzschia* be a dominant organism in natural phytoplankton blooms at sea and at the same time be a toxic nuisance to the organisms that live in those regions. Although our assessment of this situation is that there is no *a priori* evidence the *Pseudonitzschia* blooms associated with OIF experiments are harmful to the organisms from the region, we believe that study of this association should be a high priority for future OIF experimentation.

We have emphasized the relationship between OIF and *Pseudonitzschia* because there is no evidence of open ocean blooms that foster other algae that make neurotoxins. In addition, as we have mentioned, there are no

observations in the published literature of relationships between *Pseudonitzschia* and phytoplankton blooms in open ocean water that have been harmful to marine mammals or seabirds.

Biogenic trace gases and their potential impact

The Greenpeace technical note cite a letter to Science from Lawrence [Lawrence, 2002] who writes in response to the policy forum article by Chisholm et al. ([Chisholm et al., 2001] and the reply by Johnson and Karl [Johnson and Karl, 2002]. [Allsopp, 2007] mention this unreviewed letter in raising questions related to whether OIF would change the concentration of atmospheric trace gases, especially dimethyl sulfide (DMS). We will discuss DMS, the trace gas that has most frequently been measured in association with OIF, as well as the less well-studied trace gases.

Dimethyl sulfide

Dimethyl sulfide (DMS) is not a greenhouse gas, but it is radiatively active. DMS has been shown to be generated from particulate dimethylsulphoniopropionate (DMSP; an algal precursor of DMS) from phytoplankton blooms in laboratory and mesocosm experiments (e.g. [Nguyen et al., 1988], [Levasseur et al., 1996]). The Greenpeace technical note correctly mentions the fact that phytoplankton blooms, OIF and DMS are related and says that “*An increase in DMS could, in theory, work to reduce atmospheric temperature by enhancing the formation of reflected clouds, although the magnitude of any potential change is highly uncertain.*” (p. 13). Both theory [Charlson et al., 1987] and measurements [Bates et al., 1987] call attention to the relationship between DMS and marine sulfate aerosols and cloud condensation nuclei. Both theory and observation have also associated DMS with increased cloud cover that has a net cooling effect on the surface below. While the magnitude of potential changes may be uncertain, Lawrence [Lawrence, 1993] reviewed the atmospheric chemistry literature associated with the connection, highlighted the strength of the feedback and calculated on the basis of empirical evidence that it could offset as much as 20% of the thermal perturbation due to CO₂. We are not aware of any dispute in the literature that DMS is associated with cloud formation and that its effect is to cool the surface.

DMS was measured during several OIF experiments: During SOIREX Experiment [Boyd et al., 2000] observed an increase associated with the early prymnesiophyte-dominated portion of the bloom. [Turner et al., 2004] reviewed measurements of DMS in IronEx I and II, SOIREX, and EisenEx. DMS inside the OIF patches increased in all four the experiments. [Wingenter et al., 2004b] found that DMS increased in SOFEX N. The Greenpeace technical note indicates that “*a reduction in DMS was recorded in SERIES and no change was observed in SEEDS I*” (p.13). While DMS decreased in the northwest Pacific SERIES experiment, it was only after it had *increased* substantially in response to the initial phase of the bloom [Levasseur et al., 2006]:

“First, DMS concentrations tended to increase more rapidly inside the patch during the initial nanoplankton bloom, leading to DMS concentrations ca. 2 times higher inside the patch than outside on day 6. Second, DMS concentrations became consistently lower inside the patch (often below our limit of quantification of 0.03 nmol L⁻¹) than outside (ca. 6 nmol L⁻¹) during the peak of the diatom bloom.” (p.2353)

We have found no published record of the SEEDS I DMS results although they were mentioned in the summary of Takeda and Tsuda [Takeda and Tsuda, 2005] who explained that because prymnesiophytes were not prominent in the bloom it was expected that DMS would be low. Thus, the experimental data from OIF suggest that it is most likely that larger experiments or deployment would result in DMSP formation at some stage(s) of the blooms and that the DMSP would result in enhanced DMS.

It is also important to note that the lifetime of DMS in the atmosphere is short -- roughly 2 weeks during/after a bloom ([*Nguyen et al.*, 1988], [*Bates et al.*, 1992], [*Berresheim et al.*, 1998]). Since a region can probably only be fertilized once a year, the impact of DMS would be very short-lived. There is no evidence in the literature that this would be deleterious. In fact, it has been suggested as a negative feedback contributing to cooling.

While it is difficult to determine the impact of larger OIF experiments -- or even larger scale deployment of OIF on DMS, important evidence of the relationship between DMS and climate comes from the study of ice cores. Wolff et al. [*Wolff et al.*, 2006] found little change in DMS from the circum-Antarctic region preserved in ice of glacial age at Antarctic Dome C in spite of seeing substantial changes in iron dust. This iron flux has been associated with substantial productivity changes in the Southern Ocean (e.g. [*Cassar et al.*, 2007a], [*Anderson et al.*, 1998]). This would make sense if the impact of DMS were short-lived. Thus the evidence that is currently available suggests that times of great biological productivity, such as might occur during OIF experiments or larger scale deployment did not result in persistently elevated DMS concentrations.

Other biogenic gases

The scientific literature associated with other biogenic gases shows few clear relationships between them and OIF, with the exception of isoprene. Wingenter and his colleagues [*Wingenter et al.*, 2004b] found that methane, isoprene (C_5H_8), and methyl bromide (CH_3Br) increased subsequent to Fe fertilization during SOFEX, but that carbon monoxide (CO) and methyl iodide (CH_3I) did not. Liss and coauthors [*Liss et al.*, 2005] found that the concentrations of DMS and iodomethane (aka methyl iodide) were greater inside the fertilized patch at EisenEx than outside and mentioned that dibromochloromethane was greater in the patch but did not show data for it. In contrast, methyl nitrate (CH_3ONO_2) and bromoform ($CHBr_3$) showed no increase in the EisenEx fertilized patch over the concentrations outside. Moore and Wang ([*Moore and Wang*, 2006] found that isoprene, which is related to phytoplankton, increased in the SERIES patch, but that methyl iodide showed no increase in the patch. The Greenpeace technical report cites this conflicting evidence, as well as Liss and coauthors' conclusion that more measurements will be necessary in future experiments.

Thus, the information about biogenic gases other than DMS is quite mixed. While these results certainly indicate that more research is necessary to understand whether they have a clear-cut relationship to naturally occurring plankton blooms and/or to OIF stimulated blooms, we believe that there is certainly insufficient evidence on which to base any negative assessment at present.

Unintended Ecosystem Shifts

The Greenpeace technical note discusses a serious issue that has been raised several times concerning the potential that OIF, especially if conducted at large scale and/or continued for several years, would result in ecosystem shifts that could have negative consequences for ocean ecology in general and for fisheries specifically. Allsopp and her coauthors [2007] propose that “*Any changes in the phytoplankton community will have unknown and poorly predictable, but potentially highly damaging, impacts on marine ecosystems*” (Exec. Summ, p. 4). This conclusion is based on two fundamental arguments expanded on in the technical note: 1) “*iron fertilization significantly changes the composition of the phytoplankton community*” (p. 11, for which they quote [*Chisholm*, 2001], and 2) “*As a consequence of changes to the plankton community, correspondingly, marine food webs and biogeochemical cycles would be altered in unintended and unpredictable ways.*” (p. 11, for which there is no reference). We will look at each of these arguments based on the extensive literature of phytoplankton studies of both natural and iron-stimulated blooms.

First, it is important to note that 1) conclusions from coastal ecosystems cannot be extended to the open ocean phytoplankton blooms where nutrient availability and physical circulation are fundamentally different from the coastal zone (e.g. [Smayda, 1997a] and 2) to understand the basic dynamics of open ocean phytoplankton blooms. We also point out that the deep open ocean is different from lakes and shallow coastal waters in which the sediment serves as a reservoir for spores and other resting stages of the photosynthetic organisms which can be mixed into the photic zone by storm activity or seasonal changes in physical circulation [Margalef, 1963; 1978].

Natural blooms have been studied for decades, of course, and a rich literature based on theory, laboratory experiment and observations at sea and from satellite have resulted in basic empirical understanding of bloom dynamics. The most comprehensive of studies of open ocean blooms are the JGOFS process studies, which invested enormous international oceanographic expertise in evaluating the time evolution of blooms from the standpoint of photosynthesis, zooplankton dynamics, biogeochemistry, and carbon export. *These studies conclusively show that natural phytoplankton blooms in all of the major biogeographical regions of the ocean result in changes in the proportion of various species in the photosynthetic community throughout the progress of the bloom.* e.g.: JGOFS North Atlantic Bloom Experiment [Lochte et al., 1993]; JGOFS Equatorial Pacific Experiment [Barber et al., 1996]; JGOFS Arabian Sea Experiment [Shalapyonok et al., 2001]; JGOFS South Ocean Experiment [Bathmann et al., 2000]. This is because different photosynthesizers have evolved different strategies for capitalizing on the nutrient and light resources from the ocean (e.g. [Longhurst, 2006]) and because zooplankton graze picoplankton with different efficiencies than they do larger photosynthesizers like diatoms (e.g., [Morel, 1997]).

Many large regions, like the Southern Ocean, also vary in which species dominate during blooms. For example, Arrigo and coauthors [Arrigo et al., 1999] found that blooms in stratified waters of the Ross Sea were dominated by diatoms while blooms in well-mixed waters were dominated by a single species, the microalgae *Phaeocystis antarctica*. Under bloom conditions in the Atlantic Sector of the Southern Ocean, the phytoplankton assemblages were also characterized by only a few species [Laubscher et al., 1993]. However, the dominant bloom species varied from season to season with chain-forming diatoms (*Nitzschia* spp. and *Chaetoceros* spp.) dominating the assemblage during the early summer blooms and nanophytoplankton dominating the assemblages during the late summer under lower productivity conditions. Thus the species that dominate natural blooms are generally different from those that dominate under non-bloom conditions - and are species with higher photosynthetic capabilities (e.g. [Laubscher, et al., 1993].

Looking specifically to the regions that have been discussed for OIF (the North Pacific, the equatorial Pacific, and the Southern Ocean) natural blooms generally result in a succession of dominant photosynthesizers culminating with diatoms (e.g. [Smetacek et al., 1997], [Kiorboe et al., 1998], [Sarhou et al., 2005]). (Areas in the Atlantic are thought to be iron-replete because of the substantial iron-rich dust flux from the Sahara and have not generally been targeted for OIF.) These studies show that with favorable light, nutrient, and physical conditions diatoms, previously present in extremely small quantities in the surface water compared to other photosynthesizers, begin to increase their photosynthesis and growth rates and eventually become a major portion of the bloom ([Iriarte and Fryxell, 1995]; [Landry et al., 1996]; [Sarhou et al., 2005]). Barber and Hiscock (2006, p. 2) summarize these studies:

"In the open ocean, the onset of favorable nutrient, light or stability conditions elicits a characteristic response by the ambient phytoplankton assemblages: diatoms, which are initially rare or even undetectable in the ambient assemblage,

increase their specific rate of photosynthesis and specific growth rate. Within a few days, as the bloom matures, diatoms comprise the great majority of the bloom biomass.”

We have cited only a few examples of the extensive literature on phytoplankton succession during blooms, but emphasize that these results come from the analysis of *natural* blooms. *The conclusion from this peer-reviewed literature is that it is natural for phytoplankton assemblages to change during blooms. Thus, the mere occurrence of phytoplankton community changes cannot be used as an argument that OIF is deleterious.*

Let us now look at the phytoplankton dynamics results from the iron-stimulated blooms. De Baar et al (2005) emphasize that all of the OIF experiments with the exception of IronEx I (during which the bloom was subducted after four days of development) culminated in well-defined diatom blooms. Martin et al [Martin et al., 1994], Coale et al. [Coale et al., 1996], Mann and Chisholm, [Mann and Chisholm, 2000], and Landry [Landry, 2002] have studied the phytoplankton in the equatorial Pacific and Southern Ocean iron enrichment experiments. They found that the non-diatom photosynthesizers were iron limited (Mann and Chisholm 2000) and increased quickly in response to iron enrichment. After a few days they reached a higher concentration level, but ultimately were held from further increases by zooplankton grazers. Diatoms also began to increase quickly but, as is the case with natural blooms, their initial concentrations were lower and it generally took several days for them to dominate the assemblage [Barber and Hiscock, 2006].

Lindley and Barber [Lindley and Barber, 1998] have studied the response of photosynthesizers to natural iron stimulation in waters that are in the wake of the iron-rich Galapagos Island downstream circulation. They found that their response was identical to that of the IronEx II experiment. [Blain et al., 2007a] also found a succession in photosynthesizers in the natural Kerguelen Island iron enrichment. Thus, natural blooms stimulated by iron, natural blooms stimulated by increased light or nutrients, and artificially stimulated blooms all show a succession of phytoplankton, often ending 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.

What causes these changes in dominance?. There is growing evidence 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, 1963] to 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 phytoplankton 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.

What about the fate of the diatom assemblages that characterized all of the iron-stimulated blooms in the Pacific? Eventually diatoms deplete the macro or micronutrients and lose their physiologic ability to maintain buoyancy [Waite et al., 1992a; Waite et al., 1992b]. Riebesell [Riebesell, 1991] has described aggregation during a

diatom bloom. And Alldredge et al. [Alldredge et al., 1995] have also shown that diatoms can exude polymers that enhance their aggregation. Much of this early work is summarized by Turley and her co-authors ([Turley et al., 1995]). Others have highlighted the role of the skeletal material itself as a source of “ballast” that enhances export [Armstrong et al., 2001]. Sancetta and her co-authors [Sancetta et al., 1991] summarize a substantial number of examples of massive rhizosolenoid (generally pennate) diatom blooms and sinking events. Given the number of examples and the likelihood that a specific diatom bloom would be observed at sea, they concluded that mass sinking of such organism may be common. Finally, the paleoceanographic record also provides many examples of dense accumulation of diatoms in sediments from the past ([Brodie and Kemp, 1994; Kemp et al., 1995]) that are not associated with dramatic changes in ecology of the plankton recorded in sediments.

The Greenpeace technical note asserts that “*as a consequence of changes to the plankton community, correspondingly, marine food webs and biogeochemical cycles would be altered in unintended and unpredictable ways.*” (p.11, no reference) As we have shown above, there is no evidence that OIF changes the plankton community in ways that are not the norm for ocean phytoplankton blooms. Looking for evidence in other components of the foodweb, the Greenpeace technical note cites the Freeland and Whitney [Freeland and Whitney, 2000] study of salmon response to climate change in the Gulf of Alaska. That study showed that climate change was affecting plankton populations and, in turn, that salmon had decreased, potentially by starving. Allsopp and her coauthors (2007) argue that this shows that “*fundamental changes in plankton communities of this nature, however, they are induced, may have a detrimental impact on marine food webs...*” (p. 11) or that there will be a “*...knock-on negative effect on all other marine life...*”

We fail to see how a publication that shows that fish starve when phytoplankton and zooplankton in surface waters are reduced due to global warming argues against stimulating phytoplankton growth by OIF. Although we realize that this is a complex issue, the most reasonable conclusion from the article is that stimulation of phytoplankton growth might help. Indeed, this is the case in the Southern Ocean where iron released when icebergs melt supports higher productivity and a diverse community around the bergs [Smith Jr et al., 2007].

In the single case of which we are aware where the impact of OIF up the food chain to fish was studied (SEEDS), the effects 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]

This is also consistent with the historic association between diatom new production and fisheries ([Ryther, 1969], [Cushing, 1995], [Smetacek, 1998]). We are not arguing that OIF *will* enhance fisheries, but there is certainly no substantive evidence provided that enhanced diatom production in the ocean is associated with harm to food webs or *decreased* fisheries production. While we agree that this is an issue that should be studied in future experiments, the only published evidence suggests that fisheries are enhanced.

Paleoceanographic inference related to ecosystem shifts

There is substantial paleoceanographic evidence that glacial periods during the Quaternary (the past 2.4 million years) were characterized by increases in dust flux of 2-20x to the ocean (e.g., [Jickells et al., 2005b], [Winckler et al., 2008]), and accompanied by substantial increases in ocean biological productivity [Cassar et al., 2007b]. While there are certainly changes in the plankton assemblages preserved in sediments that are associated with glacial times that are different than those associated with interglacial times (e.g. [Hays et al., 1969]), there is no evidence from microfossils or pigments that these changes eliminated other species. Furthermore, while there is evidence during this time of *global* productivity changes, enhanced export [Moore et al., 2000] and lower oxygen concentrations at the sea floor, there is no evidence of anoxia [Francois et al., 2002]. If there is a bottom line from three decades of paleoceanographic study of glacial to interglacial conditions in the ocean, it is that glacial periods with enhanced iron flux result in higher productivity and CO₂ drawdown.

Downstream nutrient depletion

Another complex ecosystem issue that has been raised by Allsopp and her coauthors [Allsopp, 2007] is whether or not OIF might use nutrients in one region that support productivity in another region downstream of the fertilization site. Because such downstream impact cannot be measured directly it has been studied in models and inferences have been made about the impact of productivity changes from the paleoceanographic record.

Looking at the modeling literature, Allsopp and her coauthors argue: *"It is of great concern that results of modeling by Gnanadesikan et al. (2003) implied that commercial iron fertilization could result in non-local impacts on marine biology, i.e. long-term reduction in biological productivity over a much wider ocean area, which could have a significant negative impact on fisheries."* (p.11)

Aumont and Bopp [2006] also address the issue of downstream nutrient:

Previous studies have suggested that iron fertilization may alter the current patterns of primary productivity, even far away from the enrichment sites [Sarmiento and Orr, 1991; Gnanadesikan et al., 2003]. However, because they were using the nutrient-restoring approach, export production was predicted to drop to zero after the stop of the iron supply. Of course, as shown by our model, this result is unrealistic. Primary productivity is not decreased in the core of the HNLC regions, neither during the fertilization nor after it.

Aumont and Bopp (2006) did find that downstream nutrient depletion is likely to be more significant in non-HNLC regions (e.g. the majority of the Tropical Pacific). A further interesting observation from Aumont and Bopp (2006) is that, *"90% of the additional uptake [of carbon in the 100 year simulation] occurs in the Southern Ocean confirming the predominant role of this region."* Both results suggest that regions like the HNLC Southern Ocean are more favorable locations for OIF activities. This reinforces other recent modeling by Cassar et al. [2007] showing that the Southern Ocean is a primary carbon sink from enhanced iron delivery during glacial times. A key result of this is that downstream nutrient depletion is not likely to occur in the Southern Ocean, because the mixed layer is much deeper than the euphotic layer (the opposite of the Tropical Pacific). Therefore nutrients depleted seasonally by enhanced phytoplankton blooms are entirely replaced by the winter mixing cycle, and Aumont and Bopp note, *"maximum nitrate concentrations are not significantly altered in the Southern Ocean when iron is artificially supplied"*. Aumont and Bopp (2006) also found that total global biological

productivity increased by 20.0 GtC/yr in the first year of fertilization, and remained elevated by 9.8 GtC/yr in the 100th year of fertilization when compared to the unfertilized case.

Another recent model simulating ecology as well as biogeochemistry in OIF [Jin et al. 2008] also found no evidence of downstream nutrient depletion in OIF simulations between one-time fertilization and 10 year sustained fertilization:

Other factors, such as the “borrowing” of nutrients from other regions and other periods leading to reduced production downstream in time or space, a mechanism suggested by Gnanadesikan et al. (2003) and taken up by Aumont and Bopp (2006) can play only a minor role. If this mechanism were important, one would expect strong differences between one-time and continuous fertilizations, as the borrowing would follow different transport mechanisms (across time versus across space). No such differences are seen in our simulations, as there is little change between corresponding one-time and continuous fertilization simulations.

Winckler et al. [Winckler et al., 2008] show that increased dust flux during glacial intervals is associated with increases in biological productivity. Therefore global productivity did not seem to be limited by nutrient depletion when much of the ocean was receiving more iron in dust [Jickells et al., 2005a] .

Modeling Results

What can we learn from computational models of iron fertilization?

In the last few years, computational models of ocean iron fertilization have greatly increased in power. Iron plays a central role in the biogeochemical dynamics of the ocean and is being included in basic biogeochemical models even if they are not focused on OIF (e.g. [Tegen et al., 1996], [Mabowald et al., 1999]). Current models of the effects of iron fertilization incorporate a complex set of interactions and feedbacks in the physical, biologic, and chemical realms. This means that the models that are best able to simulate the effects of OIF must include a physical circulation model of the ocean – often coupled to an atmospheric model -- a biogeochemical model to describe how biology interacts with the chemical cycles of the ocean (e.g. carbon cycle, nitrogen cycle, iron cycle); and a model of ecosystem dynamics, that includes the growth of phytoplankton and the zooplankton that prey upon them. These models have been used to simulate time periods of decades to a century, and spatial scales of ocean basins to the entire global ocean. This capability has evolved rapidly in response to a decade of open ocean process studies on the input side and substantial increases in computing power to allow the coupling of different components (e.g. Fig. 7)

While models can illustrate aspects of both the short and long term effects of OIF, it is important to recognize that models that predict impacts of OIF activities are dependent on specific assumptions about how the ecosystem responds to OIF. Every model must make simplifications that balance the state of scientific knowledge and the available computing power. Field experiments are necessary to provide the coefficients and/or parameterizations that are translated to the formulae embedded in models and also provide data to test the accuracy of models. Finally, models have the potential to become obsolete as rapidly advancing computing power and modeling techniques allow for more realistic simulations, and as new experimental data changes their calibration. Nonetheless, the continually evolving and improving models are an essential component of the comprehensive scientific investigation of the effects of iron fertilization as a

carbon dioxide mitigation technology. Policy makers considering OIF must pay careful attention to this rapidly advancing field.

The Development of Climate models, Past, Present and Future

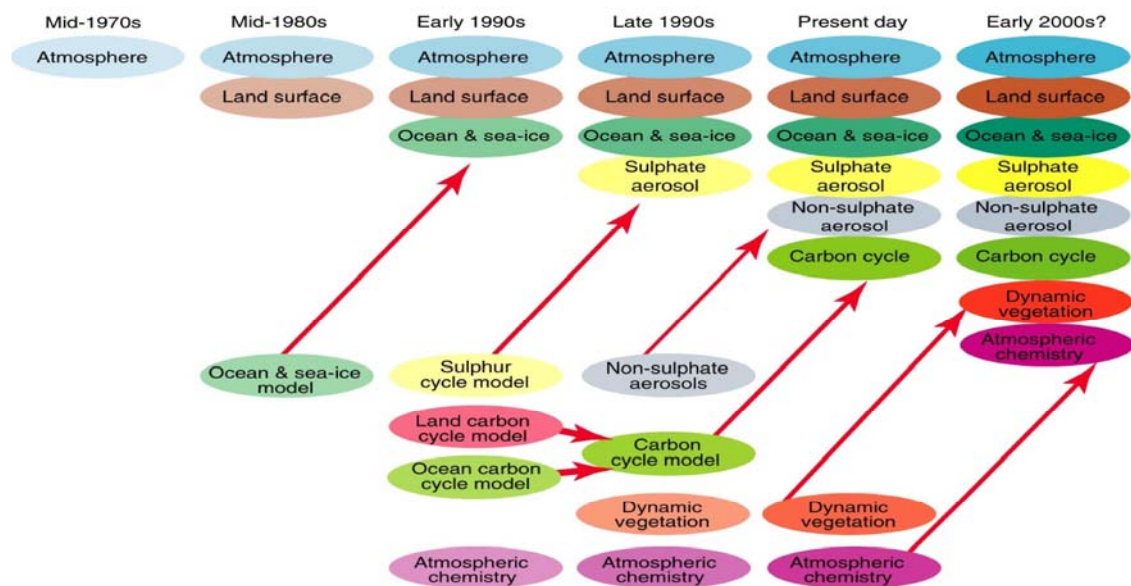


Fig. 7: An example of the development of models from Washington (2002)

Allsopp et al. [2007] cited several older modeling studies in supporting the statement that, *“the results generated by modeling studies have not generally been favorable towards using oceanic iron fertilization as a climate change mitigation strategy.”* While these studies still have significant scientific merit in terms of raising important research questions and in advancing scientific discourse, newer modeling studies must be given strong consideration when discussing OIF policy. Furthermore, new experimental data, which show significantly greater carbon export from iron-fertilized phytoplankton blooms could significantly alter the conclusions from these older models because they will result in changes to the basic export parameters ([Blain et al., 2007b]; [Buesseler et al., 2007b]; [Smetacek et al., 2007]).

We have chosen to discuss the specific results of modeling experiments in the context of specific issues that were raised in the Greenpeace technical note, but want to emphasize here the importance of following the development of modeling efforts and noting when models with greater capability of representing the ocean environment change the results of simpler models. Models are extremely important tools for simulating potential outcomes, but in the end, only experimentation at scales from which more realistic inference can be drawn can answer the complex questions related to the impacts of ocean iron fertilization.

Statements from the Science Community

Allsopp and her coauthors [Allsopp, 2007] cite a statement by the Surface Ocean Lower Atmosphere Program (SOLAS) of the International Geosphere Biosphere Program (IGBP) which concluded that:

“Ocean fertilization will be ineffective and potentially deleterious and should not be used as a strategy for offsetting carbon dioxide emissions” [Allsopp, 2007]; [SOLAS, 2007] .

Subsequent statements from the ocean science community have, we think, been more complete and have emphasized the importance of experiments to answer questions about efficacy and impact of ocean iron fertilization.

The UNESCO Intergovernmental Oceanographic Commission (IOC) recently formed an ad-hoc Consultative Group on Ocean Fertilization in part for the purpose of addressing several scientific questions posed by the International Maritime Organization (IMO) London Convention Scientific Group. Participating were several of the scientists who participated in OIF experiments, as well as one of the members of the SOLAS Scientific Steering Committee. The group endorsed additional experimentation with OIF and three principle questions regarding experimentation that had been posed by the London Convention.

What constitutes “large scale” in the ocean? The IOC statement regarding this point is: *“There is no well-established meaning to “large scale” that would allow it to usefully distinguish between activities that would and activities that would not damage the ocean environment”*

Is there justification of the need for experiments at scales of order 200km by 200km?: *“The effects on the fertilized patch of stirring and mixing with water that has not received the fertilization treatment becomes less important near the center of the patch as patch size increases. This would provide incentive to develop experiments at scales of order 200 km by 200 km, this scale being larger than that of typical ocean eddies. For the same reason, it may be easier to assess the influence of surface manipulations on the sinking fluxes of particles when the experiments are at this scale.”*

What is the assessment of the impacts on oceans of experiments at such scales? *“It is impossible to assess the impacts of experiments through information on spatial scale alone. A host of factors, including rates, amounts, concentration, duration and composition of chemical addition, location, time of year, and so on, could all jointly be determinative of ocean impacts.”*

A second scientific group, the Scientific Committee on Ocean Research (SCOR) of the International Council for Science (ICSU) asked its Group of Experts on the Scientific Aspects of Marine Environmental Pollution (GESAMP) to look into the issue of OIF. This group identified the kinds of measurements and studies that would be important to determine whether OIF sequesters carbon and to quantify its impact on the oceans. The group indicated that the results are OIF are presently unknown and may range from “the desired and positive to the unintended and negative”. This group also commended “efforts by some commercial ventures to create codes of conduct and obtain outside reviews.” This statement refers to the elements Climos has proposed for consideration in a Code of Conduct.

Finally, a group of scientists who have been involved in previous OIF experiments addressed the issue of larger scale OIF in the published literature [Buesseler *et al.*, 2008b]. These authors also call for larger

experiments with longer periods of observation and highlight the kinds of measurements and observations that will be necessary, together with modeling, to understand the potential of OIF.

We agree that further experimentation is necessary and have proposed to provide funding to the international ocean science community to carry out the appropriate experiments at a scale (~ 200 x 200 km) that would allow questions of efficacy and impact to be answered more effectively.

OIF and Commercial Involvement

Costs

While commercialization of OIF is a separate issue from its scientific efficacy and potential impacts, The Greenpeace technical note [Allsopp, 2007] suggest a large potential cost of operations (including materials and distribution), verification (including measurement, monitoring and modeling) and a low expectation of returns based on projected results derived from previous experiments.

Climos has created a detailed financial model of the expected costs involved in OIF operations and verification. While it is inappropriate to provide the details of a business plan in a document like this, it is important to highlight that our model includes the likely physical project locations (including logistically challenging locations in the Southern Ocean), expected market price of the iron sulfate required, transport and distribution costs, as well as the instrumentation and ship support required to measure, model and quantify the direct sequestration efficiency during and after the experiment. We think the data from mesoscale iron enrichment experiments as well as data from observations of natural blooms is highly instructive in modeling what costs are likely to be in all areas of activity. Clearly it makes sense to pay particular attention to those experiments where the end of the bloom and subsequent export was observed, though of course we also understand the high degree of variability in the natural environment. We have also built in costs for third party verification of samples and measurements. The model includes a full inventory of N₂O and methane levels as well as a calculation of CO₂ sequestration benefit that is net of project related emissions from materials and operations. The model assumes sequestration efficiencies based on the scientific results discussed above, not on 100% - or even 50% - of new biological productivity. We are also preparing a methodology that will be completed after discussions with the scientific participants of the first experiment and will publish the methodology prior to the first project. That document will detail the measurements, modeling and analytical techniques the project team and community feel are necessary to verify sequestration.

Of course, the risk exists that iron fertilization may not be commercially viable based on the expense involved in delivering the iron effectively to the project location and the demands of a rigorous measurement and verification program. This risk is borne knowingly by prospective commercial OIF ventures and their investors. What seems of more fundamental importance is that quantification and permanence be calculated accurately, transparently and conservatively and that these results be independently verified. These financial risks are similar to those borne by companies that are developing other types of clean technology and/or carbon mitigation projects. They, too, could be technically successful but financially unsuccessful.

Commercial appropriateness

Separate from the issue of financial cost is that of commercial appropriateness. We note that the entry of the private sector could bring substantial private capital to fund and accelerate this research. Indeed, accelerating research and stimulating innovation is a fundamental intention of the creation of global carbon markets [Sorrell and Sijm, 2003]. Further, there are many examples in other sectors, such as biotechnology and information technology, where partnerships between public and private entities resulted in a more rapid pace of invention and deployment of beneficial technology (e.g. vaccines for the developing world [Smith, 2000]).

Capital from private sources fulfills two important requirements necessary to advance the investigation of OIF as a potential climate mitigation technique. First, it provides funding for moderate scale demonstration experiments identified as necessary by the scientific community (i.e., about 200 x 200 km) that are both costly, and for which it is increasingly more difficult to obtain research grants. Second, it provides a potentially sustainable source of funding for further experimentation. In this way, conservative, verified results from previous demonstrations can fund subsequent cruises during which the ecological effects of OIF can be studied longer term.

The interest of the commercial community in funding experiments or demonstrations of this scale in order to address questions of sequestration and/or impact has led to an active discussion of the best way to ensure that the results of such experimentation can be evaluated by the scientific community that we have discussed above. An early contribution to this discussion were the elements of a Code of Conduct proposed by Climos [Climos, 2007]. The code addresses three aspects of commercial activity: regulatory concerns, carbon market concerns, and scientific/environmental concerns.

The code proposes that any commercially funded activity should be in full compliance with applicable regulatory requirements, including the use of permits required under the London Convention of 1972 and subsequent London Protocol, environmental impact assessment, and avoidance of sensitive areas such as marine protected areas, world heritage sites, etc. The purity of the iron compound being used for fertilization should also be known and should not pose a threat to marine life.

The code proposes that commercial activities should also use the best practices of the carbon markets. These would include the development of a published, validated methodology that provides detailed information on the methods of determining the carbon sequestration, independent verification of results by third parties. Other quality aspects of carbon credits, such as calculation of baselines before and after--as well as in and out--of the fertilized patch, calculation of all leakage, adherence to additionality and permanence criteria should also be characteristics of the projects. Any credits derived from experiments or demonstrations should also be tracked and registered to prevent duplicate sale.

The Climos code of conduct also proposes that scientific concerns about conduct of experiments should be addressed: individuals who are appropriately trained should make measurements with state-of-the-art techniques. All project specifications, including location, size, iron application, pre-and post-seeding conditions and observed responses, including measured export, should be published in an open format, such that results are accessible to the public. Measurement techniques should be described and raw data and final data should also be provided publicly as soon as possible after the experiment. Results should be available for publication, especially any results of experiments.

In the recent Science policy forum [Buesseler *et al.* 2008] also contribute suggestions for the conduct of projects done with a view toward future commercialization, emphasizing the need for a broader range of measurements than were characteristic of most of the early fertilization experiments, and the need for active collaboration between researchers and those with commercial interests, as well as philanthropic and government sources of funding. We agree with their assessment that credits should be sold only after sequestration and permanence can be rigorously demonstrated, and feel this is consistent with the aims of rigorous carbon market mechanisms which demand independent verification.

These types of formal dialog (published codes of conduct, editorials, workshops documents) are important contributions toward building relationships of trust between the research and business communities interested in ocean iron fertilization.

The timeline for building a relationship between business and research

The evolving landscape of ocean iron fertilization has three phases: basic research phase, focused research and development, potential deployment. The early experiments between 1993 and 2004 certainly fit into the basic research phase. They were small in scale (most about 10 x 10 km), financed by research grants. These experiments definitively showed that iron fertilization would result in phytoplankton blooms, and provided some important insights into the role of iron in biogeochemical cycling. Because most experiments were limited in duration and small in scale, they often did not observe the termination of the blooms and export of carbon.

A new phase of larger scale experiments has been called for by the science community [Boyd *et al.* 2007] [Buesseler *et al.* 2008] with explicit ideas about the measurements necessary to determine whether OIF is an effective mechanism for removing atmospheric CO₂ [Buesseler *et al.* 2008]. An Oceanus magazine article written from the recent Woods Hole Oceanographic Institution symposium on OIF summarized the feeling of many of the scientists at the symposium: “*Such experiments could be funded in partnership with commercial interests with the objective of understanding controls on sequestration, assessment of environmental impact, and modeling of permanence, atmospheric drawdown, etc.*” [Holmes, 2008]. Because the goals of credible carbon markets are congruent with those of researchers (proof of sequestration by accepted techniques, knowledge of the permanence of the sequestration, accounting for leakage, etc.) if sequestration is demonstrated, carbon offsets from these experiments can be validated, verified and marketed without impacting the quality of the science that is done or creating intellectual conflicts for researchers. This is certainly the case in forest carbon sequestration. This focused research or development phase is critical to understanding the potential of OIF.

Conclusions

We believe that we have made substantial effort to:

- 1) understand the history of biological export and its relationship to OIF, the most recent experimentation and the insight it provides concerning the “efficiency” of the biological pump, the details of the OIF experiments, and the degree to which their results were designed to answer questions of sequestration;

- 2) understand the research related to the environmental impacts of OIF; especially trying to avoid inappropriate extrapolation of results – for example, the use of coastal zone data where it is inappropriate to the open ocean; the inappropriate extrapolation of results from small experiments to larger scale activities; and the extrapolation of conflicting measurements to a single conclusion;
- 3) understand the most recent complex ocean biogeochemistry/ecology models and the applicability of models to the problem of understanding ocean iron fertilization and the limitations of models; especially trying to understand the limitations of models that do not mimic ecological processes but parameterize them (for good reason).
- 4) identify the limitations of OIF, for example, focusing on the regions that would result in the lowest potential for environmental impact, and
- 5) consider the concept of OIF in comparison with other accepted carbon sequestration techniques, all of which have advantages and disadvantages.

In contrast to the Greenpeace statement that OIF proposals derive from “*an incomplete understanding and highly simplified interpretation of current scientific knowledge*” (Allsopp 2007, *Executive Summary*), we believe that we have made an effort to understand the details of all of the literature and the field of OIF in general.

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