

In 2009 and 2010, an Indo-German scientific expedition dusted the ocean with iron to stimulate the biological pump that captures atmospheric carbon dioxide. Two onboard scientists tell the story of this controversial project. Besides raising the polemic on using geo-engineering to combat global warming, the expedition provided unprecedented knowledge about the oceans' biogeochemistry.

OCEAN IRON FERTILIZATION

Oceans play a key role in shaping global climate by regulating atmospheric concentrations of the planet-warming greenhouse gas, carbon dioxide (CO₂). However, given that fossil fuel burning has swamped the natural carbon cycle, geoscientists face the challenge of manipulating those natural processes to increase ocean uptake of CO₂ from the atmosphere. One such technique, ocean iron fertilization (OIF) seeds certain ocean regions with trace amounts of iron to stimulate growth of the microscopic plant-like organisms known as phytoplankton, which then die and sink. A vital scientific experiment, designed to further understanding of this process and its potential, generated considerable controversy and stiff opposition from some environmental groups because of its perceived dangers, even as it revealed important new findings about plankton ecology and the limitations of OIF as a way to enhance oceans' CO₂ sequestration. This paper will describe the challenges the authors faced when conducting the OIF experiment known as LOHAFEX in the southwest Atlantic Ocean in early 2009, and present its key findings.

The oceans' special role arises because they help absorb CO₂; they currently contain about fifty times the amount present in the atmosphere. During the past century, atmospheric carbon dioxide concentrations – the leading greenhouse gas – have risen by one-hundred parts per million/volume (ppm/v), equivalent to about 200 gigatonnes (Gt = 10⁹ tonnes) or nearly one-third of the total carbon in all terrestrial vegetation. Even extensive reforestation – highly unlikely in the face of increasing use of land for food and biofuels – would have only a limited effect on

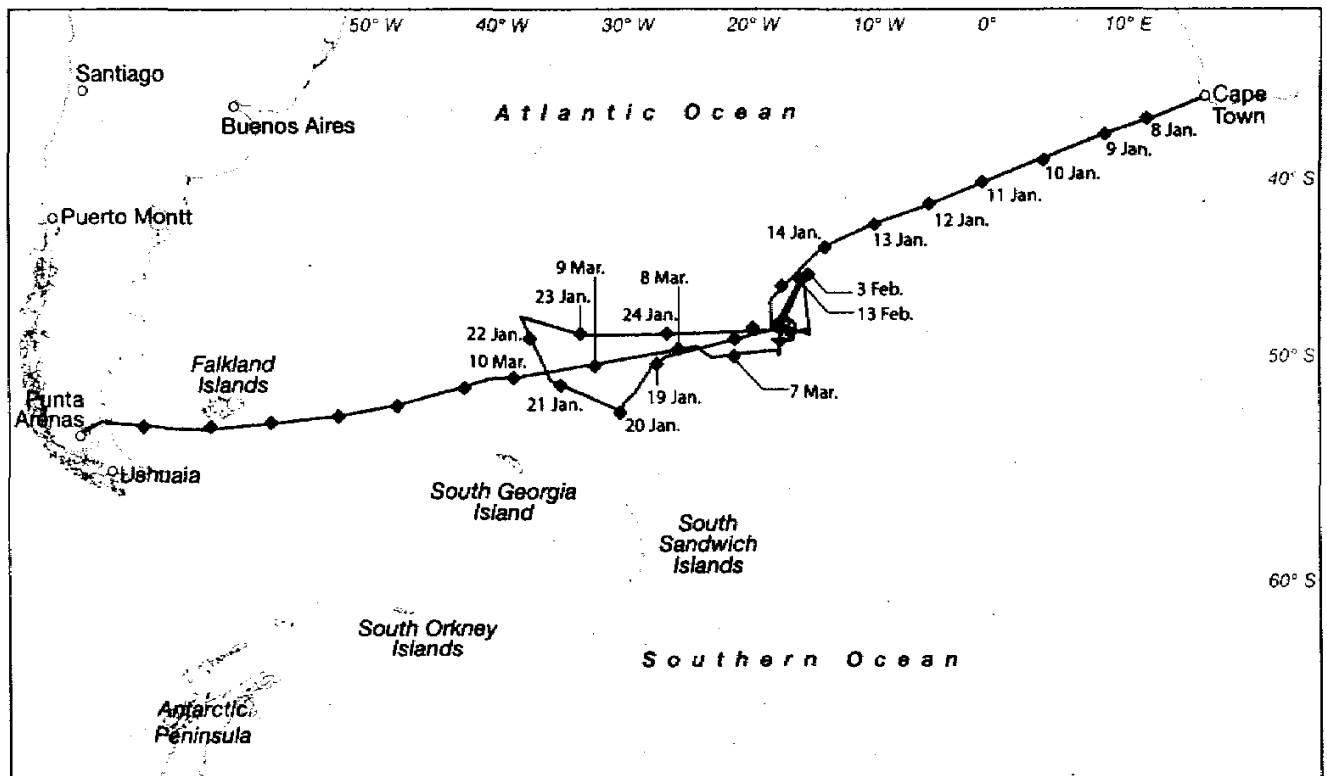
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FIGURE 1. THE LOHAFEX EXPEDITION ITINERARY



Source: The National Institute of Oceanography (Goa, India) and the Alfred Wegener Institute, (Bremerhaven, Germany)

present-day excess CO₂ levels. To mitigate ongoing global warming beyond curbing additional emissions, we advocate research on reducing atmospheric CO₂, because natural processes removing anthropogenic (human-caused) CO₂ (largely uptake by the oceans) will take thousands of years. Such endeavors, including techniques to cool the planet, are termed “geo-engineering.” A recent report by the UK Royal Society recognizes that no single measure will suffice and that it will be necessary to use a portfolio of techniques to address the growing problem (The Royal Society 2009). One possible measure is to fertilize nutrient-rich regions of the ocean with trace amounts of iron to stimulate phytoplankton growth. After blooming, the phytoplankton die and sink out of the surface layer, transferring carbon to the deep ocean and sea-floor sediments, a process called the “biological carbon pump.”

Ocean iron fertilization (OIF) experiments represent a powerful new tool to study and quantify ecological and biogeochemical processes in the ocean. The first OIF experiments were carried out in the mid-1990s: they clarified the paradox of low phytoplankton productivity in three extensive, nutrient-rich areas of the ocean at both tropical and polar latitudes (the sub-arctic Pacific, the Equatorial Pacific and the Southern Ocean). Martin (1990) proposed that phytoplankton growth rates in these regions, in particular the entire Southern Ocean, were limited by the low supply of iron (Fe) from continental sources. The hypothesis had an interesting second part related to climate: at the height of the last Ice Age, 20,000 years ago, northern

Europe and North America were covered by three-kilometre thick ice sheets; sea levels were 100 metres lower and atmospheric CO₂ concentrations were 100 ppm/v lower than those of a century ago. Martin (1990) argued that the much higher input of iron-rich dust to these regions during the cold, dry Ice Ages would have stimulated productivity and hence sequestered more CO₂ in the deep ocean than during subsequent warm, wet periods. A corollary of this “iron hypothesis” is that artificial iron fertilization of surface waters in these regions would enhance the uptake of CO₂ from the atmosphere.

The iron hypothesis was partially confirmed by a dozen experiments in all three major low-productive but nutrient-rich regions; these studies stimulated phytoplankton blooms dominated by diatoms, a group of algae with a protective shell made of silica (Boyd et al. 2007). Although natural diatom blooms are known to die and sink *en masse*, a separate experiment (the European Iron Fertilization Experiment, or EIFEX) was required to verify the fate of the iron-fertilized algal bloom. It was carried out in the closed core of a hundred-kilometre oceanic eddy that extended to the sea floor at approximately 3,500 metres. Following the iron addition, a massive bloom developed, comprised of most of the diatom species present in the surface layer. A large portion of the phytoplankton cells subsequently formed detritus flocks that sank rapidly through the deep-water column of the closed eddy core. Grazing pressure on the diatoms was surprisingly low, despite the large populations of zooplankton (tiny invertebrates) that feed on them.

Previous OIF experiments had been carried out in low-productive waters far removed from natural sources of iron, investigating the response of “oceanic desert” communities inhabited by large, spiny, thick-shelled (and hence grazer-protected) diatoms. A joint Indo-German OIF experiment, LOHAFEX,¹ conceived in 2005, focuses on the response of a very different diatom population, one that inhabits the productive Southwest Atlantic sector of the Antarctic Circumpolar Current, which is influenced by iron-enriched coastal waters. The diatoms in these waters are smaller, thinner-shelled and faster-growing than those of the oceanic deserts: they are known to sink *en masse* following blooms. A detailed investigation of these species’ distribution in the region’s underlying sediments had revealed coastal diatom species extending eastward to about 10°W (Abelmann et al. 2006). Sediments deposited during the last glacial period showed an even more extensive distribution to the east, across the entire Atlantic sector; this suggests that these diatom communities helped sequester the “missing” glacial carbon from the Ice Ages.

In 2006, we submitted the LOHAFEX proposals and, following peer-review by a number of reputed scientists in India and Germany, the project secured ship access and the necessary US\$4 million in funds, with both countries sharing the costs. Subsequently, the Alfred Wegener Institute in Germany and India’s National Institute of Oceanography prepared a memorandum of understanding (MoU) for their joint experiment. The heads of each institute’s parent organization (the Helmholtz

1. *Loha* is the Hindi word for iron.

Association and the Council of Scientific and Industrial Research, respectively) signed the MoU during a visit by the German Chancellor to India in October 2007. In addition, scientists from five institutions in Italy, Spain, the United Kingdom, France and Chile were invited, and joined, the expedition. The LOHAFEX interdisciplinary team was comprised of forty-nine scientists, with physicists, chemists and biologists participating in about equal proportions.

Open ocean experiments offer unique opportunities to study processes at space and time scales (days and kilometres) not normally investigated in standard oceanographic research cruises, which tend to be carried out along transects. A transect is a path along which one records and measures occurrences of the phenomena or processes being studied. Such processes include mixing rates of water masses, turnover rates of various chemical compounds (including climate-active gases produced by plankton), and patterns of interaction between the various groups of organisms comprising the planktonic ecosystems. This information is vital for programming complex models of ocean ecosystem functioning; developing such models will help predict how ongoing climate change will affect oceans and their biota. Organizing the various groups who will measure these processes requires careful planning and coordination. To this end, a two-week training course was held at the National Institute of Oceanography (NIO) in Goa in January and February 2008, followed by a pre-cruise preparation workshop for all participants, hosted by the NIO in April 2008.

OPPOSITION TO OIF

Shortly after the first successful OIF experiments conducted in the mid-1990s, some companies announced their intent to use OIF to acquire carbon credits on the market, as per the Kyoto Protocol. Scientists were rightfully concerned about the possible negative effects that large-scale and long-term OIF could have. These concerns – directed at commercial-scale enterprises – were voiced in opinion pieces in prominent journals (Chisholm et al. 2001; Lawrence 2002) and received considerable coverage in the media. Although the media reports were by and large accurate, the fundamental distinctions between small-scale, scientific experiments and large-scale commercial enterprises were not always stressed, resulting in a negative view of OIF amongst the informed public.

Earlier reports of heavy metals pollution and excessive phytoplankton blooms in coastal waters caused by eutrophication (Smetacek et al. 1991) had strengthened the public's concern about humans harming fragile marine ecosystems. Eutrophication occurs when water bodies are fertilized with nitrogen and phosphorus, causing excessive plant growth: over-fertilization caused by human activities often affects animal and plant populations, and degrades water and habitat quality. These concerns are entirely justified, since toxic metal pollution harms aquatic (and terrestrial) organisms, while excessive plant growth – in the form of intense surface-layer blooms followed by subsequent decay – takes up oxygen from subsurface water layers, asphyxiating local organisms. Blooms of toxic phytoplankton resulting in animal

deaths are another facet of eutrophication. Since human health is also affected, via water quality and consumption of contaminated cultivated species (mussels, fish, etc.), most developed countries had a strong incentive to adopt and pass legislation curbing pollution and eutrophication. These laws have abated the ill effects in many regions but, for largely unknown reasons, the pre-eutrophication annual cycles of plankton have not been re-established. This demonstrates how poorly we still understand the factors and processes shaping planktonic ecosystems (Smetacek and Cloern 2008). In any case, we see no justification for drawing parallels between light, small-scale additions of iron in the deep open ocean and constant, heavy doses of metals, phosphorus and nitrogen in shallower coastal areas, which definitely lead to environmental contamination and eutrophication.

In contrast to the over-fertilization and pollution of coastal areas, the open ocean often finds vital elements in short supply. All organisms require trace elements for proper metabolism – in particular iron, but also zinc, copper, cobalt, etc., in addition to macronutrients such as nitrogen and phosphate. Iron plays a key role in many basic metabolic pathways, such as synthesis of chlorophyll, reduction of nitrate to a usable form, and energy transfer. However, because of its insolubility in seawater, iron occurs at very low concentrations in a dissolved state, but abounds in sediments and soils. In coastal waters, iron concentrations are close to or even exceed their solubility maximum (a few tens to hundreds of micrograms per cubic metre); here, the supply of nitrogen is generally responsible for the limits on phytoplankton growth. However, in the open ocean, iron-limited regions where deep, nutrient-rich waters are brought to the surface by upwelling, the dissolved iron is insufficient to permit use of the other nutrients. To use a terrestrial analogy, adding iron to such regions is equivalent to watering a parched landscape where water shortage limits plant growth. All experiments have shown that iron-limited phytoplankton will increase their chlorophyll levels (i.e. become green, as do drought-stricken land plants when watered) and their photosynthetic efficiency increases, implying previous stress due to an iron shortage. Interestingly, just as the atmosphere supplies water to land via rain, it also transports iron-rich dust to the oceans (Cassar et al. 2007) with rain generally settling such dust on the oceanic surface.

As amply demonstrated by bottle experiments in the laboratory, as well as open-ocean experiments, the effects of adding iron artificially closely resemble those of natural dust input or contact with sediments. In addition to stimulating phytoplankton, added iron also acts on organisms that depend on organic matter provided by primary algae production – e.g. bacteria and various algae-feeding zooplankton, ranging from unicellular protozoa to mosquito-sized crustaceans; such organisms also increase their activity levels (Boyd et al. 2007), feeding and egg production rates. The analogy between open-ocean iron seeding and rainfall in parched land areas also holds for animals and plankton: as long as the iron dose remains light and sporadic, it mimics natural processes and does not harm the environment.

Another environmentalist concern is whether OIF could lead to blooms of toxic species, analogous to those implicated in the mass mortality of coastal animal species

– in particular fish, marine birds and mammals. We believe the risk involved must be considered in a broader environmental perspective. The vast majority of toxic phytoplankton species belong to the algal group known as dinoflagellates. Although there are many oceanic dinoflagellates, the toxic species typically occur in shallow waters, and form resting stages as spores on the sediment surface to survive unfavorable conditions. These species are more or less absent in the open ocean. However, the widespread common diatom genus *Pseudo-nitzschia*, which has some toxic species, has indeed been stimulated in OIF experiments. In a study that the Alfred Wegener Institute conducted in 2000, this genus contributed up to 25% of bloom biomass, but measurements of frozen plankton samples showed that the toxin in question – domoic acid – was absent² (Assmy et al. 2007). Blooms of toxic species of this genus regularly occur in many coastal upwelling regions: detrimental effects on marine shellfish and animals have been reported from the West and East Coasts of the United States, and off the eastern Canadian province of Prince Edward Island (WDFW 2010; CIMWI 2010). Other reports of toxic algal blooms, e.g. in the Gulf of Mexico or off the coast of Portugal, have not been linked to ill effects on marine mammals and birds; at this stage, only further experiments will show whether these toxic species pose a risk in OIF conditions.

A further environmental concern pertains to the release of trace gases in OIF experiments; we have examined and discounted the effects in greater detail elsewhere (see e.g. Smetacek and Naqvi 2008).

During 2007, unexpected developments in the international arena began to threaten the future of OIF research. The aforementioned and much-publicized announcements of corporate OIF plans alerted environmental groups, governmental and inter-governmental organizations to unregulated and premature attempts to create OIF geo-engineering. One such company aborted its plan to carry out an OIF experiment in 2007 when faced with opposition from many quarters, including nongovernmental organizations (NGOs) such as Greenpeace, the media, and governmental agencies of the countries involved. As a result, at its ninth meeting held in Bonn in May 2008, the Conference of the Parties to the Convention on Biological Diversity (CBD) adopted a resolution that:

“...urged other Governments ... to ensure that ocean fertilization activities do not take place until there is an adequate scientific basis on which to justify such activities, including assessing associated risks, and a global, transparent and effective control and regulatory mechanism is in place for these activities, with the exception of small-scale scientific research studies within coastal waters.” Such studies “... should also be subject to a thorough prior assessment of the potential impacts of the research studies on the marine environment, and be strictly controlled, and not be used for generating and selling carbon offsets or any other commercial purposes.” (CBD 2008, IX/16)

2. The domoic acid toxin is not destroyed by freezing (or cooking).

The CBD statement, interpreted by some as a *de facto* moratorium on all OIF activities, had several major flaws, as noted in June 2008 by the *ad hoc* Consultative Group on Ocean Fertilization created by the Intergovernmental Oceanographic Commission (IOC). The group expressed its concern that the CBD statement “places unnecessary and undue restriction on legitimate scientific activity” by not specifying what was meant by “small-scale,” among other things. The group further stated that “the restriction of experiments to coastal waters appears to be a new, arbitrary, and counter-productive restriction” and “there are good scientific reasons to do larger experiments” (IOC 2008). As for the regulation of OIF activities, the Consultative Group stressed that manipulative scientific experiments provide rare insight into ecosystems and “should be promoted with minimum additional bureaucratic burden;” such research should be distinguished from activities aimed at introducing additional CO₂ into the ocean (IOC 2008).

The CBD statement also “urged Parties and other Governments to act in accordance with the decision of the London Convention” (LC 1972) on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (IMO 2008). The Thirtieth Consultative Meeting of Contracting Parties to the LC and the Third Meeting of Contracting Parties to the London Protocol (LP 1996) examined issues related to ocean fertilization. It passed a resolution on 31 October 2008, which stated: “... given the present state of knowledge, ocean fertilization activities other than legitimate scientific research should not be allowed” (IMO 2008). While recognizing the need for legitimate scientific research, the attendees agreed that “scientific research proposals should be assessed on a case-by-case basis using an assessment framework to be developed by the Scientific Groups under the London Convention and Protocol” (IMO 2008). Until such a framework had been developed, Contracting Parties were “...urged to use utmost caution and the best available guidance to evaluate the scientific research proposals to ensure protection of the marine environment consistent with the Convention and Protocol” (IMO 2008). Significantly, this resolution did not seek to restrict fertilization experiments to “small-scale” and “coastal waters.” In light of the repeated references in the CBD resolution to LC/LP decisions, we – as the co-Chief Scientists of LOHAFEX, with the support of our institutions – interpreted it to mean that such restrictions no longer applied. Moreover, our proposals had gone through peer review and scrutiny by government bodies (including India’s Planning Commission). In any case, both the CBD and LC/LP resolutions are non-binding; and by November 2008 we had reached a logistical point of no return for the LOHAFEX experiment. We went ahead accordingly.

The LOHAFEX research vessel, the RV Polarstern, left Cape Town, South Africa, on 7 January 2009. The next day – to our utter surprise and dismay – an international NGO, the ETC Group (Action Group on Erosion, Technology and Concentration) wrote a letter of protest to the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (the host of the CBD meeting), claiming the LOHAFEX expedition contravened international agreements. Another NGO in Germany (Aktionskonferenz Nordsee, active in the 1990s against eutrophication

and pollution but dissolved in 2009) mobilized its former supporters to send protest emails to the Alfred Wegener Institute and the German government. The Environment Ministry responded by prevailing upon the German Federal Ministry of Education and Research to suspend the expedition. The ministries agreed to send the LOHAFEX proposal to independent research institutions (the British Antarctic Survey [BAS] in Cambridge, UK and the Leibniz Institute for Marine Sciences [IfM-GEOMAR] in Kiel, Germany) for assessment of its potential environmental impact, and to three respected legal authorities (professors of international law at German universities) for its legitimacy vis-à-vis international conventions. The proposal and the risk assessment prepared on board the research vessel and at the AWI received excellent scientific reviews from BAS and IfM-GEOMAR, and all three legal authorities argued that it did not violate international law; the German government therefore allowed the LOHAFEX expedition to continue.

THE EXPERIMENT

Following the successful technique employed in EIFEX, we had planned to fertilize a stable eddy with a closed core; this would prevent the fertilized patch from being pulled apart by currents and would maintain it over the underlying deep-water column. We made use of our enforced hiatus to examine various eddies identified from satellite images. The only suitable eddy influenced by coastal water in the entire region was centered on 16°W and 48°S. We surveyed the eddy on 25 January 2010 and received permission to go ahead with the experiment on 26 January. The next day we began fertilizing an area of approximately 300 square kilometres with ten tons of granular iron sulphate dissolved in seawater. This commercially-available ferrous sulphate is used as a lawn additive and is free of noxious impurities: the recommended dosage on land is 20 g/m². The amount needed to generate a phytoplankton bloom is 0.05 g per square metre of ocean. This yields a concentration of about 100 micrograms of iron per cubic metre over a 100-metre thick water column, well within the above-mentioned range of natural concentrations occurring in unpolluted coastal waters. Given that 10 % of sea salt is sulphate, the amount added via iron sulphate (FeSO₄) is extremely small. We tracked the fertilized patch and monitored the biogeochemical and ecological processes for thirty-eight days. The patch revolved within the eddy for twenty-three days before being ejected, after which it became elongated and diluted.

The results of LOHAFEX experiments in the productive waters of the Southwest Atlantic differed significantly from the OIF experiments in non-productive waters discussed earlier. We made six key findings: (1) diatoms were conspicuously absent due to low ambient silicate levels, and phytoplankton biomass was dominated by small (<10 µm) flagellates; (2) phytoplankton biomass did not build up beyond 1.7 milligram chlorophyll *a* per cubic metre, presumably due to intense grazing by zooplankton (concentrations of this pigment, a convenient measure of phytoplankton biomass, are approximately twice as high in big natural blooms and in previous OIF experiments in the Southern Ocean); (3) although primary productivity almost

doubled in response to fertilization, bacterial biomass and production remained low; (4) CO₂ uptake inside the patch was modest (<15 micro-atmosphere, a unit equivalent to ppm/v in the atmosphere), while organic carbon accumulated in the surface layer in particulate and dissolved forms; (5) there was little export of particulate organic matter to the deep sea; and (6) iron fertilization had little effect on the production of other climatically-important greenhouse gases, such as nitrous oxide and ozone-destroying halocarbons (carbon and halogen compounds).

The LOHAFEX experiment results have two important implications. First, although phytoplankton production in the Southern Ocean is iron-limited, supplying iron in the absence of adequate dissolved silicon for diatoms does not build up large biomass, due to top-down control by grazers. However, our results did not exclude bottom-up control due to limitation by other micronutrients, e.g. cobalt. Cobalt is an essential element required for vitamin B-12 and its concentrations reached limiting levels at the end of the experiment. Second, because silicon appears only in low concentrations over 65% of the Southern Ocean, OIF's potential for sequestering anthropogenic CO₂ is substantially smaller than previously believed. Earlier estimates, based on utilization of available nitrate, were in the order of one Gt carbon (about two ppm/v) per year; the amount of nitrate that could be used before silicate limits are reached now works out to be less than half this figure.

The LOHAFEX experiments provided novel insights into plankton ecology that would not have been achieved had research halted. However, several important issues concerning OIF remain unanswered (Buesseler et al. 2008; Smetacek and Naqvi 2008). Such questions include the role of cobalt and other trace elements, the effect on phytoplankton at times of the year when zooplankton stocks are lower, and whether longer-term OIF will affect zooplankton predators and the rest of the food chain. Like most marine scientists, we strongly oppose OIF commercialization: it is profit-oriented and less likely to respond to unforeseen negative developments – certainly less than research conducted by an international, non-profit agency under the United Nation's umbrella, closely monitored by independent scientific bodies (Smetacek and Naqvi 2008). Such an agency could be funded by the proceeds from a carbon tax rather than from a carbon credit market. We also strongly favor using this promising research methodology to address hypotheses that otherwise remain untestable. Preventing highly-controlled future OIF research, out of misplaced concerns about its environmental impacts and possible commercialization, is tantamount to throwing out the baby with the bathwater. ■

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