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Climatic effect of Southern Ocean Fe fertilization: Is the jury still out?

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[1] One of the great puzzles in oceanography has been the reason for the existence of certain areas of the world ocean like the Southern Ocean and equatorial and north Pacific where there is an abundance of unused macronutrients essential for phytoplankton growth (such as nitrate and silicic acid) [*de Baar and Boyd*, 2000]. Although physical (solar insolation and ocean surface mixing) and grazing regimes must play a part in controlling phytoplankton standing stocks in these so-called "high-nitrate low-chlorophyll" (HNLC) regions, Martin suggested that growth limitation through insufficient availability of the micronutrient iron (Fe) might also exert an important control [*Martin and Fitzwater*, 1988]. Furthermore, he proposed that stimulation of biological productivity through increased aeolian Fe delivery to the Southern Ocean at the height of the last ice age (the Last Glacial Maximum (LGM)) might have led to the concurrently low levels of atmospheric CO_2 observed [*Martin*, 1990]. The "IronEx II" open ocean Fe fertilization experiment demonstrated unequivocally the role that iron played in limiting phytoplankton growth (particularly of larger diatoms) in the equatorial Pacific [*Coale et al.*, 1996]. More recently, a similar experiment (Southern Ocean Iron Release Experiment (SOIREE)) was carried out in the Southern Ocean, a region suspected to play a key role in controlling variability in the concentration of atmospheric CO_2 over glacial-interglacial timescales [*Knox and McElroy*, 1984]. Here, too, an unambiguous response of the phytoplankton standing stock to the addition of Fe was observed [*Boyd et al.*, 2000]. However, for these changes to produce a significant response in the concentration of atmospheric CO_2, there must also be an increase in the export of carbon to the deep ocean. It is here that our understanding of biogeochemical cycling in the Southern Ocean and in particular of the potential relationships between iron supply and climate now appears to falter.

[2] In a recent article, *Charette and Buesseler* [2000] of Woods Hole Oceanographic Institu-

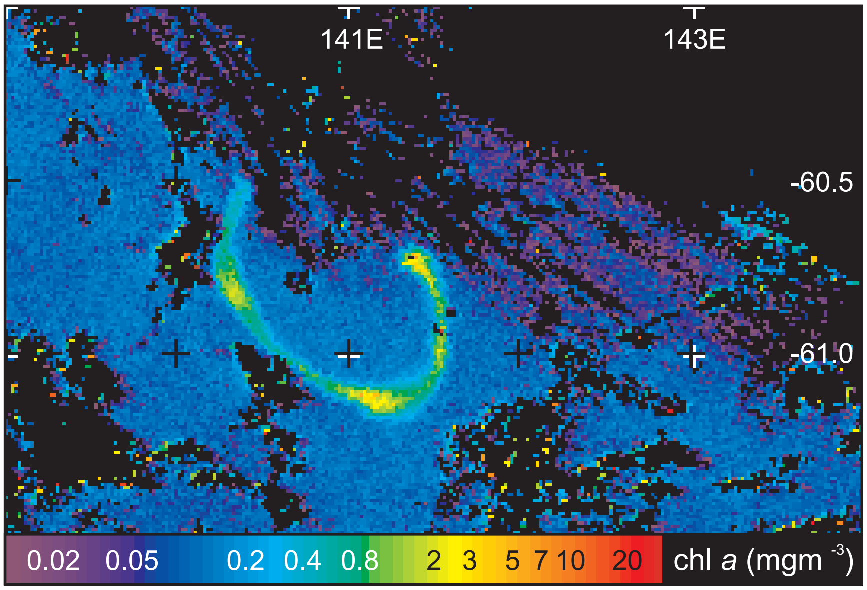

Figure 1. Image of the SOIREE bloom in the Southern Ocean in the region of 141°E 60.5°S, taken from the SeaWiFS ocean color satellite on March 23, 1999, some 6 weeks following initial Fe release.

tion carry out a thorough evaluation of particulate export from the euphotic zone (the uppermost sunlit ~100 m) during the 14-day course of SOIREE [*Charette and Buesseler*, 2000]. They chose a naturally occurring radionuclide ^{234}Th, whose concentration in a stable water column is primarily determined by a fine balance between supply (from the decay of its parent radionuclide ^{238}U) and losses due to its scavenging onto particulate organic matter (POM). Measurements of ^{234}Th concentrations in the euphotic zone both inside the fertilized area and outside of it suggest that despite the strong response in biomass to Fe addition, export of POM was virtually unaltered. *Charette and Buesseler* [2000] point out that this inertia in export response during SOIREE is not entirely unexpected. The much colder temperatures in this part of the ocean are likely to slow the response of phytoplankton to any relief of nutrient limitation. If the grazing response was similarly suppressed then the bloom succession will have been stretched out in time and final export delayed. However, complicating this intuitive explanation is the apparent persistence of the bloom (on the basis of remotely sensed elevated surface chlorophyll concentrations (see Figure 1)) for several months after the end of the experiment [*Abraham et al.*, 2000], implying that losses of Fe must have been relatively restricted over this entire period and any export therefore constrained to be modest.

[3] Does the rather ambiguous fate of the carbon fixed during SOIREE cast serious doubt on Martin's iron hypothesis for glacial times [*Martin and Fitzwater*, 1988]? As deduced by *Charette and Buesseler* [2000] from their ^{234}Th measurements, a substantial export of material (presumably associated with austral spring phytoplankton blooming) had already occurred in the region prior to the commencement of the experiment. The results of SOIREE suggest that for whatever reason, Fe addition to this post-bloom environment may not necessarily stimulate greater export. However, fertilization of natural spring blooms may have much more overall effect. These are often characterized by

intense POM export [*Bathmann et al.*, 2000]; if they were to be extended in time and/or intensified through greater Fe availability, greater draw-down in one or more macronutrients might occur, thus bringing about an increase in total POM export out of the euphotic zone. That the whole of the Southern Ocean during the LGM would have received an enhanced aeolian Fe supply persisting for thousands of years might produce a very different export response from the temporal and spatially limited experimental conditions of SOIREE. Indeed, ecosystem adaptations may have reduced the requirement for surplus macronutrients (particularly silicic acid) with prymnesiophytes such as *Phaeocystis antarctica* perhaps playing a much greater role in biological productivity [*Elderfield and Rickaby*, 2000]. In the absence of a definitive answer for the effect of Fe fertilization on export production, the role that enhanced glacial Fe supply may have played in lowering atmospheric CO_2 at that time draws some support from the apparent sequence of events surrounding the termination of each glacial period. Of all potential causative factors, only changes in dust deposition appear to precede the observed rise in CO_2 [*Broecker and Henderson*, 1998]. Furthermore, the observed relative timing between these two signals is consistent with recent carbon cycle model results [*Watson et al.*, 2000].

[4] Use of Fe fertilization of HNLC regions is starting to be seriously considered a means for the sequestration of carbon, although the considerable uncertainty surrounding the eventual fate of the fixed carbon cautions against this. Transient Fe releases may prove entirely uneconomic, particularly should extended follow-up monitoring be required to verify and quantify final carbon export. This is aside from our ignorance regarding likely knock-on effects on ecosystem structure (including commercially important fisheries). Furthermore, since intermediate depth water masses formed at these latitudes can be subsequently upwelled at lower latitudes, side-effects of chemical redistribution in the Antarctic would not be felt for some decades and may even work antagonistically to any initial CO_2 draw-down.

[5] A new Fe release experiment in the Southern Ocean underway this November aboard the research vessel *Polarstern* aims to help settle many of the issues that *Charette and Buesseler* [2000] raise with a much a longer program of observations. This is to be followed in early 2002 by the Southern Ocean Fe Experiment. Together, new observations of the eventual fate of organic matter formed at the surface will help our understanding of the processes that partition carbon to the deep ocean. This is vital not only for elucidation of the causes of past glacial-interglacial change (itself critical to our understanding of important feedbacks operating in the present-day carbon cycle [*Falkowski et al.*, 2000]) but also for the climatic consequences of anthropogenic disturbances in such a pivotal region. Hopefully, within the next few years a unanimous verdict can be delivered.

Acknowledgments

[6] The SeaWiFS data, provided by the NASA DAAC/GSFC and copyright of Orbital Imaging Corps and the NASA SeaWiFS project, was processed at CCMS-PML.

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