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ScienceDirect
Deep-Sea Research II 54 (2007) 2208–2232
DEEP-SEA RESEARCH
PART II
www.elsevier.com/locate/dsr2

^{234}Th-derived particulate organic carbon export from an island-induced phytoplankton bloom in the Southern Ocean

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Accepted 26 June 2007

Abstract

It has long been recognised that some oceanic regions have persistently low-chlorophyll levels, even though there are abundant inorganic nutrients. Studies have shown that these high-nutrient low-chlorophyll (HNLC) areas are depleted in iron, an essential micronutrient. In these regions biological production can be enhanced with artificial mesoscale iron fertilisation. However, the ability of iron-induced blooms to efficiently sequester carbon to mesopelagic depths is still an open question. It is hypothesised that sub-Antarctic islands in the HNLC Southern Ocean are also a source of iron and thus fuel the natural phytoplankton blooms observed in their proximity, thereby enhancing levels of particulate organic carbon (POC) export. To test the third part of this hypothesis, POC export was measured in the Southern Ocean region of the Crozet Islands (52°E, 46°S) during the austral summer of 2004/2005 as part of the CROZEX project. Based on satellite imagery, a high-chlorophyll region (maximum concentration $= 4\,\mu g\,l^{-1}$) north and downstream of the islands was distinguished from a low-chlorophyll region (typical concentration $= 0.3\,\mu g\,l^{-1}$) south and upstream of the islands. POC export estimates were obtained by using the naturally occurring particle-reactive radionuclide tracer ^{234}Th. POC export was initially $15\,mmol\,C\,m^{-2}\,d^{-1}$ in the high-chlorophyll bloom region, compared with $5\,mmol\,C\,m^{-2}\,d^{-1}$ in the low-chlorophyll, non-bloom region. After a moderately small bloom at the southern control stations (max concentration $= 0.7\,\mu g\,l^{-1}$) the spatial variability in POC export was lost, resulting in equally high levels of POC export (*ca.* $20\,mmol\,C\,m^{-2}\,d^{-1}$) throughout the study region. Comparison of ^{234}Th-derived POC export with estimates of new production, calculated from nitrate budgets, revealed evidence for a decoupling of new and export production, with this effect most apparent within the northern bloom area. In addition to methodological issues this apparent decoupling of new and export production could be due to a buildup of dissolved organic nitrogen within the bloom region, thus reducing the amount of POC available for export to mesopelagic depths.

Keywords: CROZEX; Crozet; Southern Ocean; ^{234}Th; Carbon export; POC

1. Introduction

The role of the Southern Ocean in the global carbon cycle has come under increased scrutiny since the publication of the "iron hypothesis" by Martin (1990). Martin hypothesised that iron was a

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doi:10.1016/j.dsr2.2007.06.002

limiting micronutrient in high-nutrient low-chlorophyll (HNLC) ocean regions, and this has since been validated in various locations by artificial, *in situ* iron-fertilisation experiments (Martin et al., 1994; Coale et al., 1996, 2004; Boyd et al., 2000, 2004; Gervais et al., 2002; Tsuda et al., 2003; Hoffmann et al., 2006). The Southern Ocean is one such iron-limited HNLC area (Martin et al., 1990) and is of particular interest not only because it covers such a large area *ca*. $20 \times 10^6\,km^2$ (6% of total ocean area) but also because it has the potential to play a significant role in the global carbon cycle. Current estimates suggest that the Southern Ocean is responsible for the uptake of about $1\,Gt\,C\,yr^{-1}$ (Metzl et al., 1999), approximately 1% of the $90\,Gt\,C\,yr^{-1}$ taken up by the world's oceans annually (Prentice et al., 2001). However, models indicate that this figure has the potential to rise to 6–30 $Gt\,C\,yr^{-1}$ given a scenario of complete nutrient utilisation supported by iron-replete conditions (Sarmiento and Orr, 1991).

The ability to induce phytoplankton blooms with the addition of iron raised hopes that it may be possible to sequester anthropogenic CO_2 in the deep ocean (Martin, 1990). By increasing phytoplankton productivity and the activity of the biological pump with the addition of iron, CO_2 could be drawn down from the atmosphere and therefore help reduce atmospheric CO_2 levels (Joos et al., 1991). However, determining whether iron fertilisation could be used to reduce atmospheric CO_2 has been an elusive question to answer (Zeebe and Archer, 2005, 2006; Chisholm et al., 2001; Johnson and Karl, 2002). Even though there remains continued discussion in the scientific literature as to whether iron fertilisation is a feasible strategy to sequester anthropogenic CO_2 (Buesseler and Boyd, 2003), the impetus and need to understand the effects of iron on phytoplankton productivity and the biological pump should be no less great.

To date, four iron-fertilisation experiments have been carried out in the Southern Ocean (Boyd et al., 2000; Gervais et al., 2002; Coale et al., 2004; Hoffmann et al., 2006), but the extent to which iron-induced blooms can sequester carbon to the deep ocean is still poorly constrained (Nodder et al., 2001; Charette and Buesseler, 2000; Buesseler et al., 2005; Bishop et al., 2004; Rutgers van der Loeff and Vöge, 2001). This is possibly because carbon export may continue to occur for some time period after the initial fertilisation by iron (Buesseler and Boyd, 2003; Buesseler et al., 2005), a time period that has been poorly sampled.

Artificial iron-fertilisation experiments have focussed on just the alleviation of iron limitation by adding iron in the form of $FeSO_4$. Although these elegant experiments have successfully shown the *in situ* link between iron enrichment and enhanced productivity, they are nonetheless simple perturbations of complex natural systems. Therefore, in addition to artificial iron-fertilisation experiments, recent years have seen efforts to try to understand the effects of natural iron fertilisation in HNLC regions. In natural fertilisation experiments the marine environment is probably influenced by a range of terrigeneous micronutrients. This contrasts with artificial iron-fertilisation experiments in which the concentration of only one micronutrient is changed. The challenge with natural fertilisation experiments will be to establish links between specific micronutrients and environmental responses to their injection.

The existence of large-scale blooms in the Southern Ocean tied to topographic features is clearly observable with satellite imagery (see Fig. 1 in Pollard et al., 2007a) and it is hypothesised that these blooms are sustained by a point source release of lithogenic iron into the surrounding waters. The most notable of these are austral summer blooms associated with South Georgia, Crozet and Kerguelen (Bucciarelli et al., 2001; Pollard et al., 2002; Korb and Whitehouse, 2004). Evidence supporting this hypothesis for the Kerguelen Islands and South Georgia has been reported by Blain et al. (2001, 2007) and Holeton et al. (2005), respectively. In studying these areas it may be possible to better understand the implications of iron fertilisation and thereby improve our ability to assess the response and efficiency of the biological pump to inputs of iron.

The focus of the CROZet natural iron bloom and EXport experiment (CROZEX) project is the annual bloom observed to the north of the Crozet Islands situated in the Indian sector of the Southern Ocean (Pollard and Sanders, 2006; Pollard et al., 2007b). Pollard et al. (2002) have hypothesised that this area is likely to be fertilised with iron from the plateau, giving rise to iron-replete conditions that induce a phytoplankton bloom in this otherwise HNLC region. The multidisciplinary CROZEX project aimed to survey the pervasive phytoplankton bloom to the north of the Crozet Islands and test the hypothesis that the islands and surrounding plateau are a source of bioavailable iron. In addition to an extensive physical hydrographic