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Patch evolution and the biogeochemical impact of entrainment during an iron fertilisation experiment in the sub-Arctic Pacific

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Abstract

An in situ mesoscale iron-fertilisation experiment in the eastern sub-Arctic Pacific (SERIES) was undertaken to test the Iron Hypothesis, that increasing iron supply would stimulate phytoplankton production and particulate organic carbon (POC) export to deep water. Patch dispersion was monitored for 26 days, using an inert tracer (SF_6) and biological tracers (chlorophyll-*a* and fCO_2), and we examine the vertical and lateral evolution of the patch, and the influence of dilution on the biological and biogeochemical response to iron addition. Vertical dispersion of the added iron was initially restricted to the upper 12 m by near-surface stratification, although the vertical flux to the lower mixed layer at this time significantly exceeded the unperturbed rate of iron supply. Calculation of vertical diffusion rates (K_z) provided an estimate of the unperturbed Fe flux across the seasonal pycnocline of 0.3–1.5 nmol/m^2/d. The iron/tracer patch partially advected around an anticyclonic Haida Eddy that originated off the west coast of Canada in 1999–2000. Lateral patch evolution was initially dominated by current strain, stretching it into a filament of ~300 km^2 by day 11 and reaching a maximum area of 1300 km^2 by day 23. Sustained high winds and intrusion of external waters between days 11 and 18 altered patch geometry and advection. Two scenarios for patch evolution are presented of a single exponential dilution at 0.1/d, and a variable dilution in which dilution increased from 0.078/d to 0.16/d (days 11–18) before decreasing to 0.05/d. Dilution rates were used to constrain dissolved iron dynamics, with iron regeneration rates indirectly estimated from biological iron uptake and lateral dilution losses. Lateral entrainment supplied ~6–7 μmol/L silicic acid and 4.6 μmol/L nitrate to the patch centre by day 20, equivalent to 37% and 45%, respectively, of total biological uptake. Indirect estimates of phytoplankton nitrate uptake from patch dilution indicated a maximum rate of 1.4 μmol/L/d, in agreement with measured rates. The cumulative entrainment of 392–500 mmol dissolved inorganic carbon (DIC)/m^2 at the patch centre by day 20 was of the same order as the total biological DIC uptake and POC accumulation. The potential impacts of a mid-experiment increase in dilution were explored; these included elevated entrainment of silicic acid when concentrations in the patch were growth limiting for

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phytoplankton, and decreased cell aggregation. Both factors could potentially have delayed the onset of bloom termination and export, and increased the longevity of the SERIES phytoplankton bloom.

Keywords: Dilution; Iron; Phytoplankton; Nutrient limitation; Nitrate; Silicic acid

1. Introduction

Iron availability is now established as a major factor determining phytoplankton biomass and community composition in one-third of the global ocean. The first tenet of Martin's iron hypothesis, that iron availability limits growth (Martin, 1990), has been confirmed in two of the three major high-nutrient low-chlorophyll (HNLC) regions, the Equatorial Pacific and the Southern Ocean (Coale et al., 1996; Boyd et al., 2000). Several lines of evidence, including iron measurements and budgets (Martin et al., 1989), in vivo experiments (Martin et al., 1989; Boyd et al., 1996), and the coincidence of blooms with elevated aeolian Fe input (Boyd et al., 1998) indicate that the third major HNLC region, the sub-Arctic Pacific, is potentially iron-limited. This was recently confirmed by a significant increase in phytoplankton biomass in response to in situ iron addition in the Western Pacific (Tsuda et al., 2003). A subsequent in situ mesoscale iron experiment was undertaken in the Gulf of Alaska (SERIES, sub-Arctic Ecosystem Response to Iron-Enrichment Study) to confirm algal iron limitation across the sub-Arctic Pacific region. A further objective was to validate the second tenet of Martin's hypothesis, that increasing iron supply would stimulate vertical export of particulate organic carbon (POC), by monitoring the decline phase of the phytoplankton bloom. The SERIES experiment, which lasted 26 days and involved coordinated operations on three research vessels, unequivocally confirmed the first tenet, with a 15-fold increase in chlorophyll. However, whereas vertical POC export increased at the end of the experiment, only a small proportion of the total iron-induced algal carbon fixed was transferred below the permanent thermocline, with the majority being remineralised at shallow depths (Boyd et al., 2004).

The linkage between perturbation and export in SERIES demonstrates that in situ fertilisation experiments have come of age, as the framework of a mesoscale Lagrangian addition currently provides the only approach to quantitatively relate a known amount of added iron to the total carbon fixed and exported from the surface mixed-layer. The approach of in situ mesoscale addition was initially adopted for iron-limitation studies to counter the limitations of in vivo experiments in which containment and surface effects, artificial mixing and light climate and exclusion of large grazers were significant artefacts. However, unlike mesocosms or bottle experiments, in situ *iron* fertilisation experiments are unenclosed with the result that dilution of the patch negates monitoring of ecosystem response at a fixed constant iron concentration. Instead, the iron concentration and the parameters that respond to it exhibit a gradient from the fertilised patch centre (the IN station) to waters outside the patch (OUT station), with resultant exchange between the two. Recent observations from iron addition experiments have begun to highlight the importance of constraining mixing and dilution of the patch (Abraham et al., 2000; Coale et al., 2004). Mixing in the surface ocean historically has been regarded as primarily determined by diffusion (Okubo, 1971), and at certain sites, such as at the centre of an eddy where current shear is minimal, this assumption is largely correct. However, it is now recognised that horizontal dispersal of a tracer is controlled by stirring, with a tracer patch typically elongating and folding into filaments in response to local current strain (Eckart, 1948; Garrett, 1983), as observed in ocean-colour images and mesoscale tracer experiments (Abraham et al., 2000). In in situ iron fertilisation experiments the mechanism and rate of mixing will influence both the biological response to the iron and its manifestation. For example, a tracer patch that is subject to zero or low current strain will diffuse in all directions, making it easier to locate and monitor than a strain-dominated patch that evolves into a long filament. However, this may have the reverse effect in terms of biological response; dilution at an eddy centre may result in initially rapid lateral loss of added iron, or other perturbant, from the patch centre so limiting the accumulation of biomass (Law et al., 2005), whereas