3 EXTENDED ABSTRACTS OF THE 2004 WORKSHOP

3.1 Synthesis of the Iron Enrichment Experiments: SEEDS and SERIES

Iron fertilization experiment in the western subarctic Pacific (SEEDS)

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The **S**ubarctic Pacific Iron **E**xperiment for the **E**cosystem **D**ynamics **S**tudy (SEEDS) was conducted in the western subarctic Pacific (48.5°N, 165°E) from July 18 to August 1, 2001 (Fig. 1). The experiment consisted of a single addition of 350 kg iron as $FeSO_4$ with 0.48 M of an inert tracer gas sulphur hexafluoride, over an 8 × 10 km patch.

Concentrations of dissolved iron increased to 1.88 nM just after the iron injection, and subsequently decreased rapidly to 0.99 nM on Day 2. After this first rapid decreasing phase, the loss rate gradually decreased, and the iron concentration did not fall below about 0.15 nM, even after phytoplankton bloom development. The added iron stayed in the surface mixed layer in particulate form throughout the observation.

The first response of phytoplankton to iron input was observed on Day 2 as the increase in the photochemical quantum efficiencies of algal photosystem II (F_v/F_m) measurements of a fast repetition rate fluorometer. The increase in phytoplankton biomass became significant from Day 6 and exponentially increased to about 20 mg m^{-3} in chlorophyll-*a* concentrations until Day 10 (Fig. 2). After that, a relatively constant biomass of phytoplankton was observed from Day 9 to the end of the observation (Day 13).

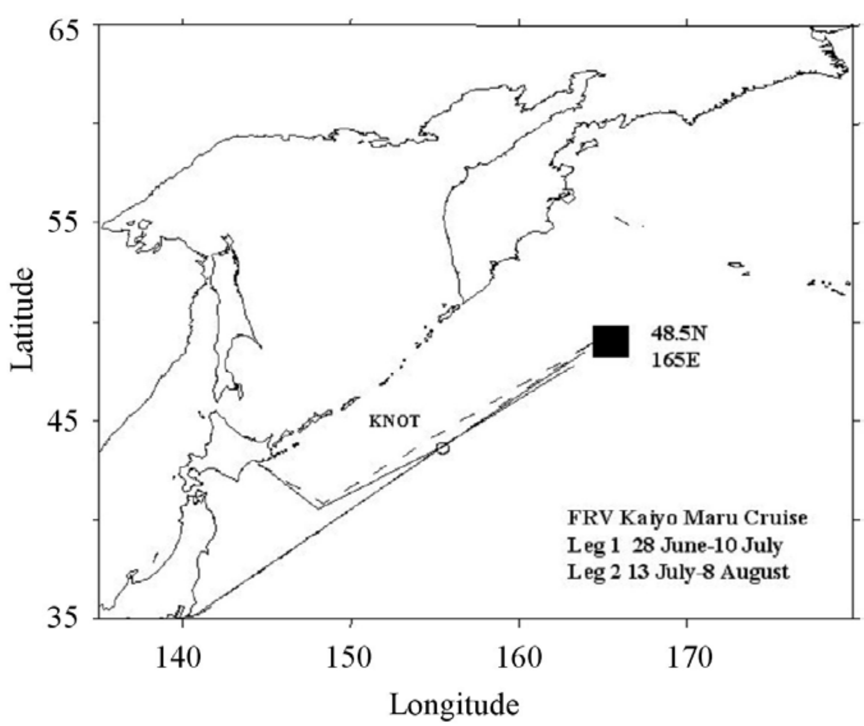

Fig. 1 Location of the iron enriched area of SEEDS, conducted in 2001, in the western subarctic Pacific.

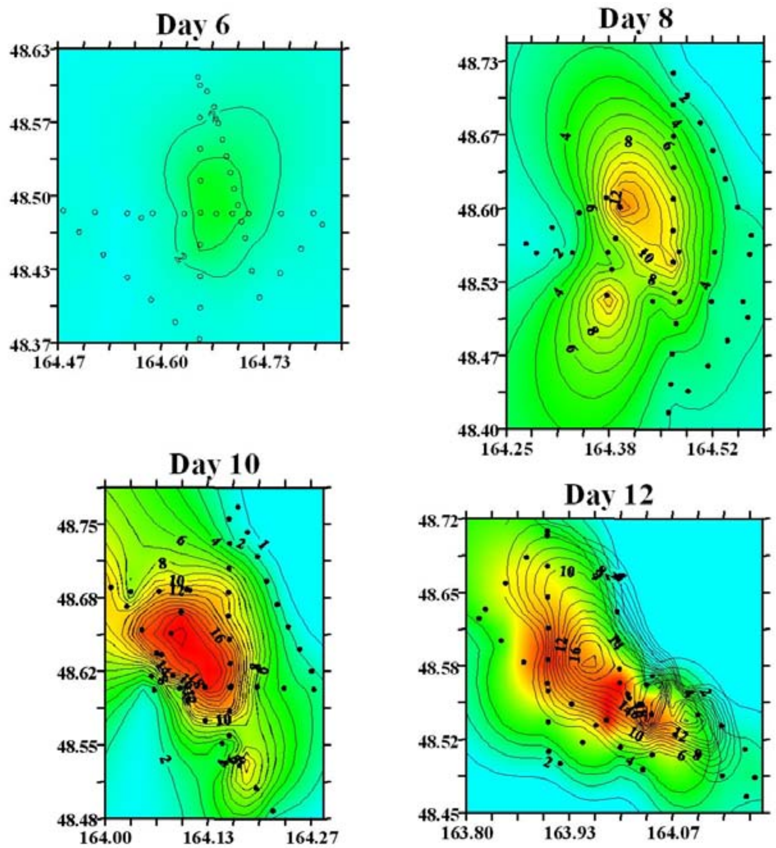

Fig. 2 Chlorophyll-*a* concentration in the surface layer of the iron-enriched patch during SEEDS.

In addition, the iron supply led to floristic shifts which resulted in the dominance of chain-forming, large centric diatoms. The fast growth and accumulation of large centric diatoms had not been observed in the earlier iron fertilization experiments conducted in the equatorial Pacific and the Southern Ocean. This large increase of phytoplankton standing stock was accompanied by large drawdowns of macronutrients, pCO_2, and dissolved inorganic carbon (DIC). Figure 3 shows that nitrate was abundant at 18 µM before the iron fertilization. The absolute nitrate uptake rate at 5 m depth sharply increased by 20 times after Day 7. The change of pCO_2 inside the iron patch was observed after Day 5. The maximum differences of pCO_2 and nitrate concentration in the surface water between inside and outside of the patch were 170 ppm and 11.7 µM, respectively, which were observed on Day 12.

High export flux of carbon in the patch was observed between Days 10 and 12 (Fig. 4). However, the export flux measured with drifting traps in the patch was not significantly different from that outside of the patch. The export flux between Day 2 and Day 13 was 12.6% of the integrated primary production in the patch. Moreover, the increase of particulate organic carbon (POC) content in the surface mixed layer was 78% of the decrease in DIC and influx of CO_2 from the sea surface. These results suggest that a major part of the fixed carbon still stayed in the surface mixed layer as particulate matter at the end of our observations. We were not able to determine, through lack of data, if the still-remaining organic matter had ultimately settled down, or decomposed in the mixed layer after our observations.

Highlights of this experiment have been published as Tsuda *et al.* (2003) and Nishioka *et al*. (2003), and other results have been published as 13 original papers in a special issue of *Progress in Oceanography* (2005, Volume **64**).

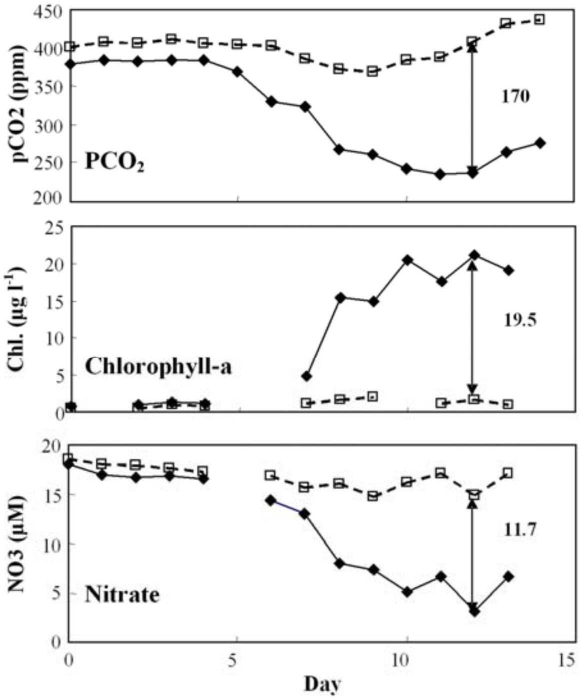

Fig. 3 Temporal changes of *p*CO2, chlorophyll-*a*, and nitrate concentrations at 5 m depth inside (filled symbols with solid lines) and outside (open symbols with broken lines) of the iron-enriched patch during the SEEDS.

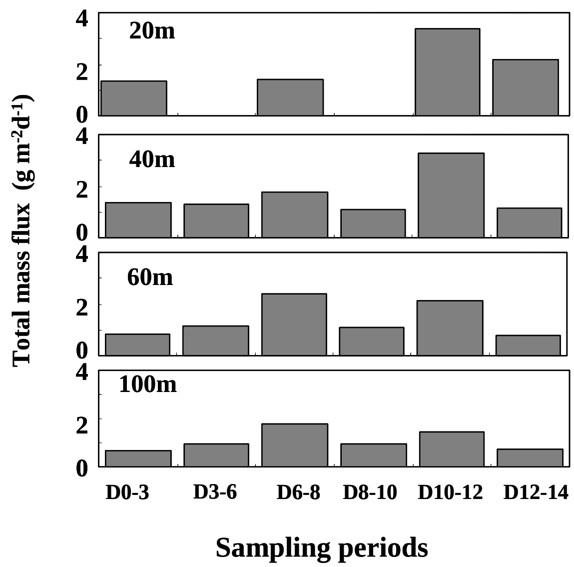

Fig. 4 Temporal changes of mass flux in the iron-enriched patch during SEEDS.

References

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The response of N and Si to iron enrichment in the Northeast Pacific Ocean: Results from SERIES

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Abstract

An iron enrichment experiment (**S**ubarctic **E**cosystem **R**esponse to **I**ron **E**nrichment **S**tudy), SERIES was carried out at Ocean Station Papa (50°N, 145°W) in the subarctic Northeast Pacific Ocean in July 2002, in order to observe the physiological, ecological and biogeochemical responses to a release from iron stress in these high-nitrate, low-chlorophyll (HNLC) waters. The patch was created by injecting $FeSO_4 \cdot 7H_2O$ (iron source) and SF_6 (water mass tracer) into the ship's wake while a Lagrangian grid of 8 km × 8 km was navigated. During the 27 days of occupation after iron release, the patch grew from < 100 km^2 to approximately 1000 km^2, and at Days 15–16 of the experiment, the patch shifted from a northward to an eastward drift, towards the centre of an eroded eddy. Shortly after, salinity and nutrient concentrations below ~10 m depth began to increase and, simultaneously (and possibly coincidentally), the iron-induced diatom bloom crashed. Mass balances of nitrogen and silicon were performed for two periods, separated at Day 20, when mixed-layer nutrient concentrations began to increase. Prior to Day 20, drawdown of silicic acid and nitrate was 13 μM and 5 μM, respectively, in the upper 30 m. $Si[OH]_4$ drawdown was balanced by biogenic silica (BSi) accumulation in the upper 50 m and sediment-trap flux at 50 m (export flux), while NO_3^- drawdown was balanced by the accumulation of particulate organic nitrogen (PON) and NH_4, and PON export flux. Because of the injection of nutrients below ~10 m after Day 20, nutrient drawdown was not observed for the latter part of the experiment, but there was a large decrease in BSi and PON concentrations in the upper 50 m. The decrease in BSi concentration was balanced by sediment-trap fluxes of BSi, but the decrease in PON concentration exceeded the sum of NH_4^+ accumulation and PON export flux. The imbalance in the nitrogen budget might be attributable to the poor constraint of changes in the dissolved organic nitrogen (DON) pool, or by the fact that dilution during patch growth has not been considered. These latter factors are the focus of on-going work.

Introduction

Over the past decade, mesoscale iron enrichment experiments have been performed to test the hypotheses that iron limits phytoplankton growth in HNLC regions of the world's oceans (*e.g.*, Gran, 1931; Martin and Fitzwater, 1988), and that greater wind-driven iron delivery to these regions during glacial periods resulted in higher primary production and organic carbon export, leading to the increased sequestration of carbon in deep oceanic waters and relatively low atmospheric CO_2 concentration during glacial times (Martin, 1990). All previous iron enrichment experiments have resulted in significant photosynthetic responses, and thus have demonstrated iron limitation in HNLC waters. However, bloom termination and export from the mixed layer have been observed only for the SERIES experiment. In some cases, the lack of such observations prior to SERIES is because physical conditions deteriorated the patch (IronEx I, EisenEx), but more generally the reason why the fate of iron-induced blooms had not been observed is because patch occupation had to be terminated before the end of the bloom (IronEx II, SOIREE, SOFeX north and south, SEEDS). During SERIES, the bloom crashed relatively quickly (by Day 20) and the drifting sediment-trap deployments caught much of the bloom export.

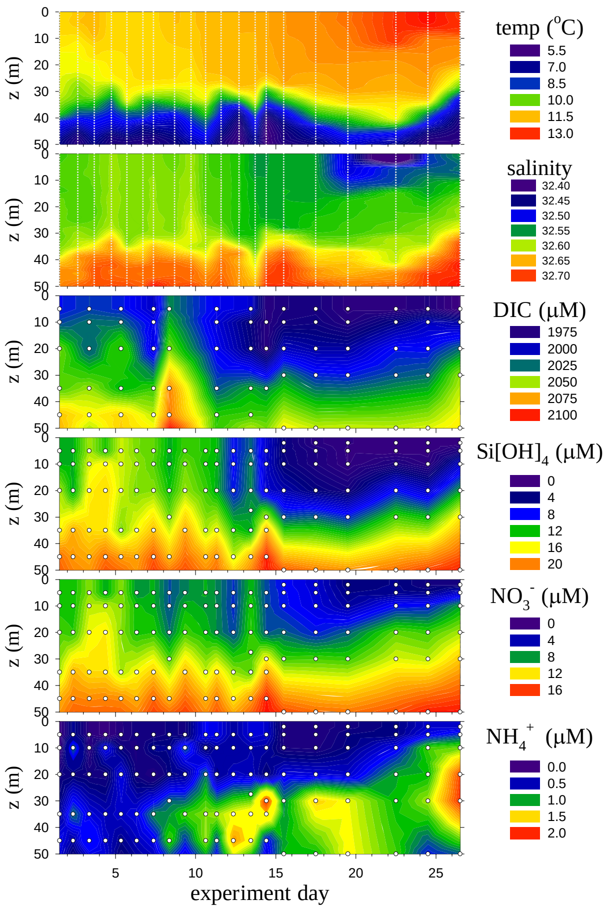

Fig. 1 Contour plots of temperature, salinity, dissolved inorganic carbon (DIC), $Si[OH]_4$, NO_3^- and ammonium (NH_4^+) for "IN" stations during SERIES. Sampling locations are denoted as points on the plots; T and S were collected at higher resolution (1 m) than for the nutrients (~10 m). Note high salinities between 10 and 30 m depth, beginning at Day 18, and the accompanying high nutrients.

Results and discussion

Several features of the iron patch are highlighted by the contour plots of Figure 1. In the upper 10 m, seasonal warming caused temperatures to increase. Salinity decreased as the patch migrated northeastward and surface nutrients (DIC, $Si[OH]_4$, NO_3^-) decreased throughout the occupation. However, beginning ~Day 18, relatively high salinity waters intruded into the patch below ~10 m bringing with them DIC, $Si[OH]_4$ and NO_3^- such that, integrated to 30 m depth, nutrient concentrations increased from Day 20 to the end of the occupation (not shown). Although these nutrient increases might be interpreted as a remineralisation signal, other evidence that they were advected into the patch with the high salinity waters is the increase in NO_3^- in the euphotic zone. Heterotrophic degradation oxidizes organic nitrogen to NH_4^+ which is then oxidized to NO_3^- by light-inhibited nitrifying bacteria, so that NH_4^+ oxidation occurs primarily below the euphotic zone. Here, NH_4^+ is used as a remineralisation signal.

For given time and depth intervals, mass balances account for changes in silicon and nitrogen for each pool in which these elements can be found. If changes in each pool are appropriately quantified, their sums should balance input and export of the elements from the volume of water being considered. Three events define the time periods of our mass-balance considerations. A mixing event occurred around Day 3, and led to the decision for a second iron addition, as the wind event resulted in low *in situ* iron concentrations. Period 1 (Tables 1 and 2) begins at Day 3. The shift from nutrient drawdown to nutrient accumulation at Day 20 marks the end of our period 1 and the beginning of period 2. The end of the occupation on Day 27 is the end of period 2.

There are two pools of silicon in the marine environment: dissolved $Si[OH]_4$ and particulate BSi. Within acceptable error, changes in these pools in the upper water column balance export fluxes of BSi for periods 1 and 2 (Table 1). $\Delta Si[OH]_4$ for the upper 50 m is ~25% greater than for the 30 m integral. Positive Si fluxes balance negative fluxes for both periods.

Table 1 Mass balance of silicon for experiment Days 3–20 (T_1) and 20–27 (T_2).

	$\Delta Si[OH]_4$	ΔBSi	BSi export
T_1	–390	240	130
T_2	0	–160	130

Note: All values are in mmol Si m^{-2} $period^{-1}$. $\Delta Si[OH]_4$ is for the upper 30 m, ΔBSi is for the upper 50 m, and BSi export is to sediment traps at 50 m depth.

Nitrogen mass balances are more complicated because this element resides in more pools than does silicon. The major nitrogen pools are NO_3^-, PON, dissolved organic N (DON) and NH_4^+. N_2 gas is by far the largest pool of nitrogen in seawater, but is assumed to have been biologically and chemically unreactive during SERIES. The nitrogen budget during SERIES balances for period 1, but during period 2 the large loss of PON was not balanced by NH_4^+ accumulation and PON export (Table 2). ΔNO_3 for the upper 50 m is ~20% greater than for 30 m integral. Positive nitrogen fluxes balance negative fluxes for period 1, but not period 2. We are currently working on better quantification of the DON pool during SERIES, and results might improve the nitrogen balance for period 2.

Table 2 Mass balance of nitrogen for experiment Days 3–20 (T_1) and 20–27 (T_2).

	ΔNO_3	ΔPON	ΔNH_4	ΔDON	PON export
T_1	–160	39	24	45?	35
T_2	0	–82	26	???	22

Note: All values are mmol N m^{-2} $period^{-1}$. ΔNO_3^- is for the upper 30 m, ΔPON, ΔNH_4^+, and ΔDON are for the upper 50 m, and PON export is to sediment traps at 50 m depth.

Also, we have not quantified mixing with waters outside the patch. The general effect of mixing will be to make negative fluxes (nutrient uptake; Tables 1 and 2) more negative, and positive fluxes (particulate accumulation and export) more positive, so that consideration of mixing should not have a large effect on the balance of the budgets of Tables 1 and 2. However, better consideration of mixing will generate more accurate fluxes and may improve the balance of the budgets.

Summary

Iron enrichment in the subarctic Northeast Pacific (Ocean Station Papa) resulted in a significant photosynthetic response by iron-stressed phytoplankton. Nutrients (DIC, $Si[OH]_4$, NO_3^-) decreased throughout the bloom in the upper 10 m, but below 10 m depth began to increase after Day 18 due to the intrusion of a high-salinity water mass. Mass balances of nitrogen and silicon are generally good, but ongoing work will better quantify changes in the pool of dissolved organic nitrogen, and will account for mixing with waters outside the patch.

References

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