B-57 Subarctic Pacific Iron Experiment for Ecosystem Dynamics Study (SEEDS) (Abstract of the Final Report)

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1. Introduction and Research Objectives

Iron limitation has been proposed as the reason for the existence of surface waters rich in macro-nutrients but low in phytoplankton biomass in the subarctic Pacific, the equatorial Pacific and the Southern Ocean. Recent *in-situ* iron enrichment experiments confirmed this in the equatorial Pacific and the Southern Ocean[1)2)3)]. In the subarctic Pacific, with biology and water structure different from the other two regions, strong zonal gradients in atmospheric iron deposition exist between the eastern and western gyres, which may give rise to distinct phytoplankton communities that characterize these biogeochemical provinces. Here we present an overview of SEEDS (Subarctic Pacific Iron Experiment for Ecosystem Dynamics Study), the first *in situ* test of the iron limitation hypothesis on natural ecosystem and geochemical cycles in the subarctic Pacific[4)], and SERIES (Subarctic Ecosystem Response to Iron Enrichment Study) in the eastern subarctic Pacific. The SEEDS 2001 and SERIES 2002 were originally proposed in the Advisory Panel on Iron Fertilization Experiment (IFEP) at the PICES Eighth Annual Meeting in Vladivostok, Russia, and are now recognized as activities of IGBP- SOLAS (Surface Ocean and Lower Atmospheric Study).

2. Results

2-(1) SEEDS 2001

FRV *Kaiyo Maru* of Fisheries Agency of Japan departed from Tokyo on 28 June. Seventeen researchers from Fisheries Research Agency, National Institute for Environmental Studies, Hokkaido University, University of Kyoto and University of Tokyo participated the cruise. The first leg of the cruise was allotted for physical and biochemical survey of the target area, and performance tests of newly designed equipment such as continuous measurement system of an inert tracer gas sulphur hexafluoride (SF_6) and iron/SF_6 mixing and injection system.

During the second leg of the cruise, a meso-scale *in-situ* iron-enrichment experiment was conducted in the western subarctic gyre of the North Pacific (48.5°N, 165°E) from 18 July to 1

August 2001 (Fig. 1). The experiment consisted of a single addition of 350 kg iron as $FeSO_4$ (10,800 L of 0.5 M Fe) with 4100 L of SF_6 saturated seawater, over an 8×10 km patch with a mixed layer depth of 10 to 15 m. Using the GPS buoy-Lagrangian navigation system, the solution of iron and SF_6 mixed at a constant ratio was released after the ship's propellers within 23 hours. Initial concentration of dissolved iron in the iron-enriched patch was about 1.9 nM (mean value of day 1 underway transect; maximum recorded was 6.0 nM).

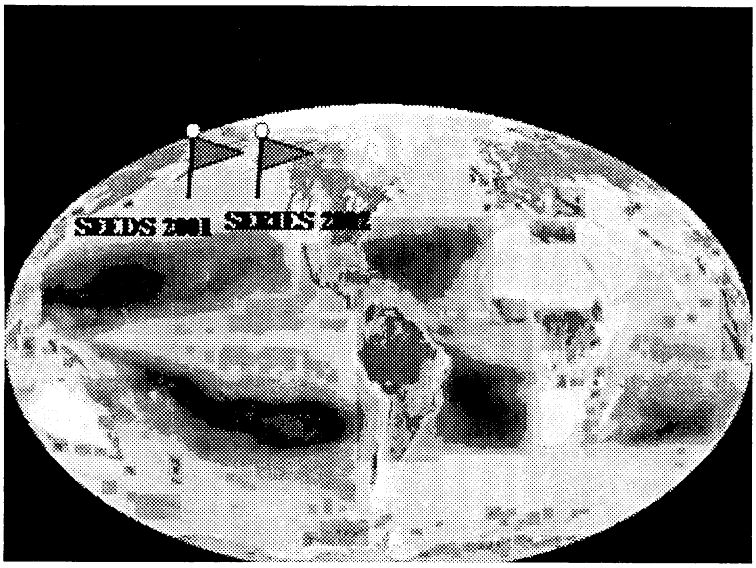

Fig. 1. Locations of the iron-fertilization experiments (SEEDS, SERIES) in the North Pacific.

The weather was fogy but calm throughout the observation period. The iron-enriched patch moved westward during the experiment, but we could successfully trace the iron-enriched patch for 2 weeks by measuring SF_6 in surface waters. Along with continuous surface measurements of SF_6 and iron concentrations, a fast repetitive-rate (FRR) fluorometer, which measures community photosynthetic competency (F_v/F_m), and an underway pCO_2 system also provided real-time mapping. The first indication of a phytoplankton response to iron enrichment was a significant increase in F_v/F_m measured by FRR fluorometer on day 3 night. By day 10, we observed unambiguous and massive biogeochemical responses to the iron addition, which resulted in an increase in chlorophyll-*a* concentrations to as high as 17 $\mu g\ l^{-1}$ and large drawdowns in pCO_2 and nutrients .

The iron-enriched water became a rich-soup of phytoplankton and change of water color was recognizable for everyone after day 9. In addition, iron supply led to floristic shifts that resulted in the dominance of chain-forming large centric diatoms, unlike the equatorial Pacific and the Southern Ocean where iron stimulated the growth of pennate diatoms. Before the iron input, multiple species of pennate and centric diatom dominate in the phytoplankton community, but a centric diatom *Chaetoceros debilis* showed a very high growth rate (about 3 doublings a day) and occupied 95 % of microphytoplankton cells at the end of the observation. We finished up our observation with trawl sampling of salmons and other nekton in and out the patch on day 14. The water mass with high chlorophyll and low pCO_2 was still there, but we had to leave due to the limiting ship-time. Carbon budget in the iron-patch was estimated from these observations and concluded that most of carbon assimilated to the phytoplankton stayed in the surface mixing layer as particulate matters (phytoplankton and zooplankton) during the experimental period.

Our initial findings clearly demonstrate that iron availability fundamentally controls the magnitude of phytoplankton response in high nutrient areas of the western subarctic Pacific. Analysis of samples from this experiment will also help to clarify the role of iron plays in regulating the biogeochemical processes such as export production.

2-(2) SERIES 2002

SERIES was part of a collaborative project between Japan and Canadian SOLAS funded by NSERC (Natural Science and Engineering Research Council), CFCAS (Canadian Foundation for Climate and Atmospheric Science) and DFO (Department of Fisheries Ocean Canada). By using three ships and staggering their schedules, we extended the observation of the iron-enriched patch to the longest period to date.

Iron injection was performed on July 9, 2002 at near the Stn P (Fig. 1, 50°09'N, 144°45'W) using an expanding square method. Initial value of dissolved iron was 4nM as expected. Although the iron started to decrease soon after the injection, the biological responses were much slower than the SEEDS. After the stormy weather chlorophyll-*a* increased 2-fold of the initial value, therefore the second injection of iron was performed on July 16. But it was not until the research vessel *J.P Tully* left and *Kaiyo Maru* arrived that the chlorophyll-*a* value peaked (July 24-26) at around 6 mg m^{-3}. At the same time there was a large drawdown of silicic acid and pCO_2. In this period, a good SeaWiFS satellite image was obtained fortunately, showing the drastic difference in water color between the iron-enriched patch and natural surrounding waters (Fig. 2).

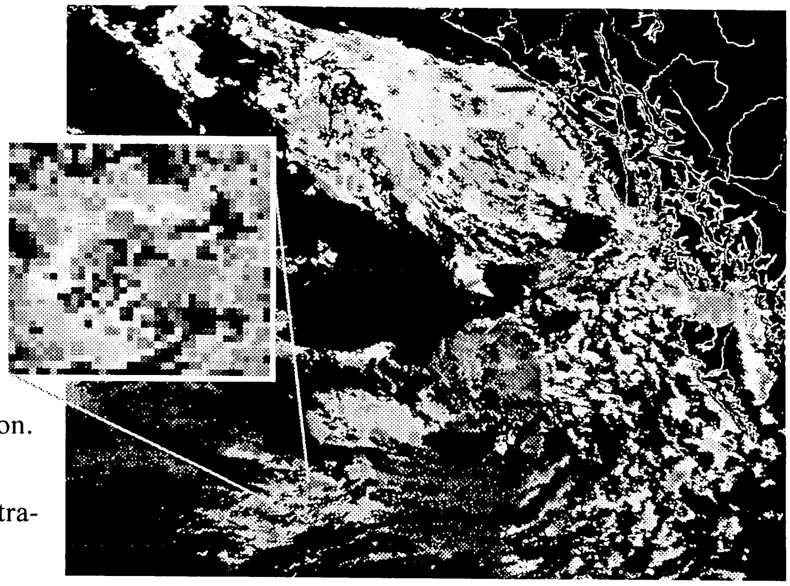

Fig. 2. Iron-fertilized area in SERIES observed by satellite (SeaWiFS) on 29 July, 2002 (21th day from the fertilization. The area was indicated By chlorophyll concentration over 3 mg m^{-3}.

Kaiyo Maru and Japanese participants continued to monitor the patch until August 4, giving 26 days of coverage of the patch. The observed period was divided into tow phases: The first phase was characterized by lower standing stocks of phytoplankton, production of *DMS* (dimethyl sulphide) and dominance of haptophycae. The second phase was characterized by high biomass of phytoplankton, low production of DMS and dominance of diatoms. Dominant diatom species were pennate diatoms such as *Pseudonitzschia* and *Neodenticula* with some centric diatoms, which was different from SEEDS results. Sediment trap deployments showed no increase during the observation of *J.P. Tully*. However, *Kaiyo Maru* observed significant increases of sinking materials at all depths indicating a flux of particulate matter out of the surface layer. At the same timing, ammonia, which is a degradation product of organic matter, increased even in the surface layer in the later period of the *Kaiyo Maru* observation. The increased flux of organic carbon is expected to continue for 3days after our leave, supported by a theoretically calculated sinking rates of diatoms, then 50% of the assimilated carbon by phytoplankton is estimated to sink to the deeper layers[5)].

3. Discussion

3-(1) Comparisons between the eastern and the western gyres

Fast and intensive response of diatoms in the SEEDS comparing to that of SERIES and other iron-fertilization experiments were the most prominent characteristic in these studies. In the SEEDS, chain-forming centric diatom, *Ch. debilis* increased from < 1 to over 10000 cells ml^{-1} during the observation period (13d). *Ch. debilis* is known as a neritic species forming a resting spore. Other neritic diatom species also showed high growth rates from the initial period from the iron fertilization. These findings suggest that fast and intensive response in the western subarctic Pacific is caused by the existence of neritic diatom species in the area and shallow surface mixed layer (10-20 m) compared with those of the western gyre and other experiments (Fig. 3).

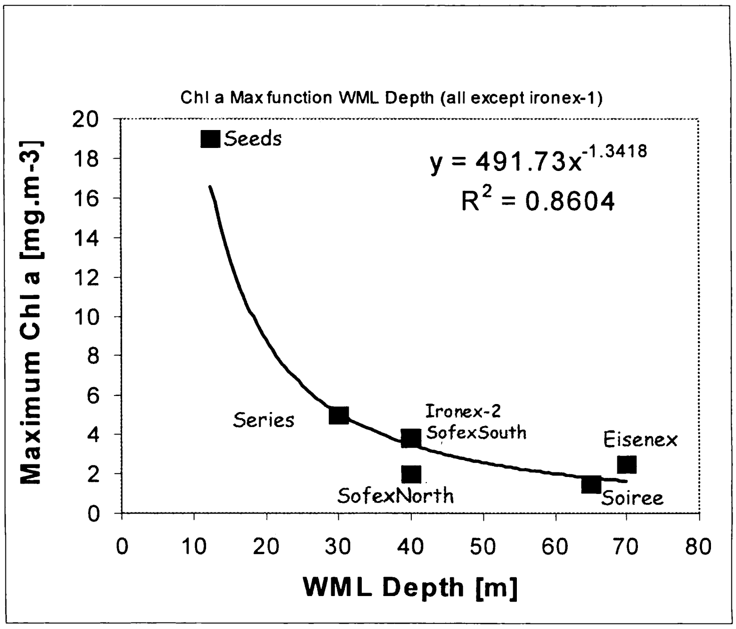

Fig. 3 Maximum concentration of chlorophyll-a as a function of the surface mixed layer depth in the iron-fertilization experiment. (summarized by Dr de Baar)

Another difference of the two experiments was the production of DMS. High production of DMS was observed during the haptophytes blooming period (before the diatom accumulation) in the SERIES, but we could not detect any significant difference of DMS production in the SEEDS. These differences in the response to iron fertilization are primary caused by the species composition of both areas. Moreover, we consider that difference in the species composition is caused by the gradient of natural iron input rate from atmosphere and the subsurface layer[6)]

3-(2) Evaluation of iron fertilization as a way for carbon sequestration

We could not determine the efficiency of iron fertilization as a way of carbon sequestration in the SEEDS, because we did not observed significant increase of export flux compared with outside of the patch. Seventy-eight percent of the fixed carbon was stayed as particulate matter in the surface layer at the end of the observation (d13), suggesting that the observation period was too short to estimate the fate of the carbon. In the SERIES, significant increase of the export flux was observed but 50% of the fixed carbon was remineralized by the hetrotrophic activity during the 26days period. A preliminary model predicts that 40% of the fixed carbon would be exported at maximum during 40 days from the fertilization. These estimates suggest that real efficiency (export carbon/ fixed carbon) would be much lower than 100%, and would range between 20 to 40%.

3-(3) Effects of iron fertilization to the pelagic ecosystems

Phytoplankton species successions were observed in the both experiments. In the SEEDS almost a monopoly by the neritic diatom was achieved after 10 days from the fertilization. In the SERIES, haptophytes bloom and diatom bloom with multiple species were sequentially observed accompanied with DMS production and drawdown of pCO_2 and nutrients, respectively. Such a floristic shifts have been observed in the all iron-fertilization experiments, however, different species and taxonomic groups have been recognized to form blooms in each area. The size and taxonomic group of the blooming phytoplankton gives large modifications of the material flows in each area. These finding suggest that initial species composition largely determine the responses of phytoplankton community to the iron-inputs, and modify the biogeochemical cycles in the surface ocean.

In contrast, zooplankton, mainly copepods, did not show significant increases of their biomass and species compositions in both experiments. However, increases of juvenile copepods in the surface layer and increases of developmental rates of the dominant copepods were observed in SEEDS and SERIES, respectively. Different phenomenon observed in the two experiments is considered to be caused by the same mechanism. Improved food availability caused by the diatom blooming suggested to increases the survival rate of the copepod juveniles and developmental rates. These facts suggest that iron-fertilization have a positive effect on the mesozooplankton production. However, subarctic zooplankton species have their defined phenology, then large-scale iron fertilization is suspected to give considerable damages to some species of zooplankton. Moreover, iron-fertilization altered the concentration of nutrients and their ratio. Silicic acid were more rapidly consumed by phytoplankton, and complete depletion of silisic acid was observed in SERIES. Modification of ratio of nutrients concentration and depletions after the diatom bloom would have significant changes of production mechanisms in these areas.

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