

## PICES-IFEP Workshop on

### "In-situ iron enrichment experiments in the eastern and western subarctic Pacific"

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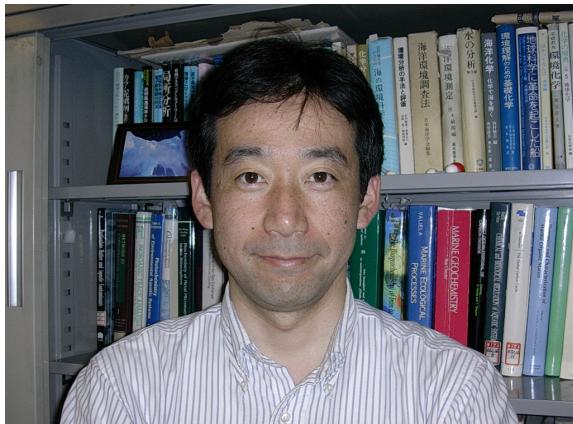
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Iron deficiency has been proposed as the reason for the existence of surface waters rich in macro-nutrients but low in phytoplankton biomass in the subarctic Pacific, the equatorial Pacific and the Southern Ocean. In summer of 2001, an iron enrichment experiment (Subarctic Pacific Iron Experiment for Ecosystem Dynamics Study – SEEDS-I) was performed in the western subarctic Pacific; and in summer of 2002, another iron enrichment experiment (Subarctic Ecosystem Response to Iron Enrichment Study - SERIES) was carried out in the eastern subarctic Pacific. These international collaborative projects between Canada and Japan were conceived at the first planning workshop of the PICES Advisory Panel on *Iron Fertilization Experiment* (IFEP), held in Tsukuba, Japan, in 2000, in conjunction with PICES IX.

In order to review the results and outstanding questions from these experiments and to discuss plans for the second longer-term experiment in the western subarctic Pacific (SEEDS-II), the PICES-IFEP Workshop on "*In situ* iron enrichment experiments in the eastern and western subarctic Pacific" was held February 11-13, 2004, at the

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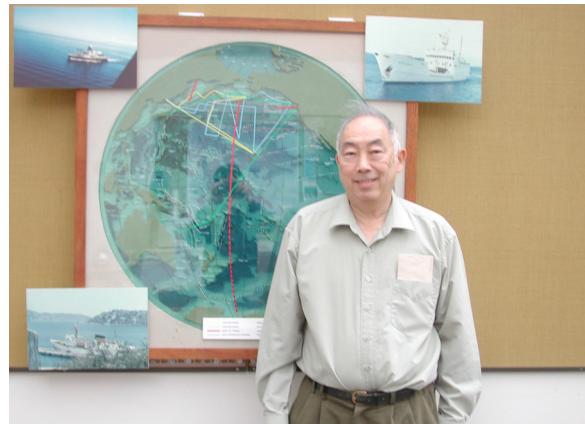
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Chateau Victoria Hotel, Victoria, British Columbia, Canada. 26 scientists from Canada, Japan, and the United States of America attended the workshop (Fig. 1).

The objectives of the workshop were to:

- Synthesize results from the two *in situ* iron enrichment experiments performed in the eastern and western subarctic Pacific (SEEDS-I and SERIES);
- Discuss responses to iron additions in lower and higher trophic levels, carbon cycles, trace-gas production and ocean-atmosphere flux, and models;
- Determine similarities and differences in biogeochemical and ecosystem responses to iron addition between the eastern and western subarctic Pacific;
- Identify specific scientific questions for the new longer-term experiment in the western subarctic Pacific (SEEDS-II).

The workshop started with 4 synthesis talks on SEEDS-I, SERIES and SOFeX, followed by 14 shorter presentations



*Fig. 1 Workshop participants at the entrance of the Chateau Victoria Hotel.*

on the physical behavior of the Fe-enriched patch, biological/physiological responses, food-web dynamics, chemistry of iron, carbon cycle, and model prediction.

#### ***What have we learned from the enrichment experiments?***

Both SEEDS-I and SERIES have demonstrated increased productivity and biomass of phytoplankton as a response to the iron enrichment. Bloom evolution and decline was captured in detail during SERIES. However, there are differences in the physical and chemical environments, the plankton ecosystem and dominant species, and zonal iron gradient between the Western Subarctic Gyre (WSG) and the Alaskan Gyre (AG). From SEEDS-I and SERIES, we can point out the following similarities and differences in biogeochemical and ecosystem responses to iron addition:

#### **Similarities**

- Diatom bloom occurred; floristic shift to large cells;
- Vertically-integrated Chl-*a* and primary production increased;
- Heterotrophic dinoflagellates grazed on diatoms after the development of the bloom, and led to significant loss of diatoms in the mixed layer;
- Copepods were not the primary grazers; SERIES was not well matched with the spring period of maximum diatom grazing (*Neocalanus plumchrus*);
- DOC (dissolved organic carbon) increased during the growth phase of bloom, was constant through the stationary phase, and decreased during the bloom decline; DOC production was about 10% of primary production;
- Increased dissolved-Fe was mainly in colloidal fraction;

- Dissolved-Fe concentration decreased rapidly by colloidal aggregation and biological uptake (less), and loss rate gradually decreased;
- Particulate-Fe concentrations remained high; bioavailability of remaining iron (mainly particulate) was low;
- Majority of macro-nutrients were consumed;
- Increase in Si/NO<sub>3</sub> drawdown ratio was observed after occurrence of physiological stress such as iron and light limitations.

#### **Differences**

- A larger and faster response (in terms of biomass) was observed in WSG;
- Initial diatom populations largely neritic for WSG and pelagic for AG; neritic species responded quickly to the iron enrichment and built up a large biomass, suggesting that the presence of coastal species as resting spores or cells is important in determining the magnitude of bloom evolution;
- The bloom was characterized by two ecological phases in SERIES. Phase I consisted of nano-phytoplankton (prymnesiophytes) and occurred before day 10 of the experiment, and phase II was mainly diatoms and began after day 10;
- Sediment traps collected large CaCO<sub>3</sub> fluxes after phase I, and high biogenic-Si and POC fluxes after phase II during SERIES, but not in SEEDS-I. SEEDS-I occupation may have been too short to observe export event;
- >50% of the mixed-layer POC (particulate organic carbon) deficit attributed to bacterial re-mineralization and meso-zooplankton grazing in AG; NH<sub>4</sub> in surface waters increased throughout the bloom;

- Characteristics of organic ligands changed rapidly upon Fe enrichment in WSG; ligands concentration tracked dissolved-Fe concentration in AG, rapidly disappearing together with dissolved-Fe concentration;
- The iron enrichment created a bloom of DMSP-rich nano-phytoplankton (*E. huxleyi*) which crashed after day 11 in SERIES, but no significant increase in DMS/DMSP was observed in WSG;
- The Fe-induced increase in DMSP had no clear effect on DMS concentrations in AG;
- The iron-induced deficit in DMS concentrations during the peak of the diatom bloom resulted from a decrease in biological DMS net production in AG.

Kenneth Coale was invited to give a synthesis talk on Southern Ocean Iron Experiment (SOFeX), which was performed in 2002, to investigate the effects of iron enrichment in regions with high and low concentrations of silicic acid. He identified the following questions to be resolved in future experiments.

- What are Fe:C:Si:N:P uptake and re-generation stoichiometries? How are these stoichiometries related to phytoplankton community structure?
- What is the steady-state condition? Is this a relevant question?
- What is the periodicity and magnitude of natural iron enrichment, both seasonally and inter-annually, and on glacial-interglacial time scales?
- What is the effect of iron enrichment on the geochemistry (low O<sub>2</sub> and de-nitrification) and ecology (nitrification) below and within the Fe patch?
- Do ecosystems respond in a natural manner to artificial Fe enrichments? What are the similarities and differences between natural and artificial Fe supply?

### ***What are outstanding questions?***

SEEDS-II is the second meso-scale iron enrichment experiment in WSG designed to investigate the longer-term effects of iron enrichment on plankton ecosystem, carbon export and trace gas production. SEEDS-II will involve about 50 researchers from universities and government institutions in Japan, the United States and Canada. The iron-enriched patch will be monitored by two ships, the R/V *Hakuho Maru* (Japan) and the R/V *Kilo Moana* (U.S.A.), for 34 days from July 21 to August 23, 2004. Through the integration and synthesis of the findings from SEEDS-I, SERIES and SOFeX, the workshop participants identified the following key themes and key scientific questions for the SEEDS-II experiment.

### **Fate of carbon**

- What portions of organic carbon fixed by coastal centric diatoms in WSG will be exported from the surface mixed layer, and what portions will be regenerated?

- To what extent would heterotrophic dinoflagellates (*Gyrodinium*) respire Fe-induced carbon fixation?
- What is turnover time of produced DOC?
- What are community respiration rates?
- Is C:N:P:Si regeneration ratios in surface and subsurface layers crucial to our understanding of Fe-induced ecological response and nutrient dynamics?
- Is biological patchiness in species and export within the patch significant?
- How does physical dilution from outside affect the patch chemistry and biology? What is the effect of dilution on budget calculations?

### **Ecosystem responses**

- Why did SEEDS-I and SERIES have opposite trends in dominant diatom composition?
- What is the role of cell lysis on changes in available nutrients, sources of DMSP, bacterial community structure and iron chemistry?
- What roles will sinking and grazing play in the decline of the bloom?
- What is the long-term effect of Fe availability on the ecosystem? How is the response to further iron addition affected?
- The ecological response to iron enrichment is largely determined by the seed population. What will the species variability and ecosystem differences be between iron-induced blooms in the same location?
- How predictable will the species response be to iron addition?
- Why does Fe addition to bottles result in N-limitation, but the large-scale Fe additions show Si-depletion?

### **Seasonal timing**

- If natural events occur, should we try to emulate those that occur at other times of the year?
- What is the importance of the presence of endemic zooplankton at the time of iron enrichment?

### **Fe biogeochemistry**

- What controls iron retention and loss after iron release?
- What is the main source of ligands production? How does it respond to iron enrichment?
- What is the role of iron ligands in Fe bioavailability and recycling?
- What is the role of Fe(II) in the phytoplankton bloom?
- What is the uptake of iron by different biota?
- What is the difference between single and multiple iron additions, and their effect on availability of iron?
- Comparison with natural iron supply: labile particulate iron was significantly higher in the surface mixed layer in WSG, but dissolved iron was at the same level as in the eastern region.
- Is bioavailability of iron (not total iron input) most important for ecosystem response?

#### Trace-gas production

- What is the fate of DMSP? Is it consumed by bacteria? Does it sink?
- What are the roles of physiological stress, Fe availability, light and macronutrients on DMSP cycling?
- What is the extent of emission to atmosphere?

#### *Recommendations for SEEDS-II*

- It was recommended to lengthen the experiment if possible; the decline will depend on patch physical dynamics, bloom dynamics, etc.
- Additional suite of measurements is required to study bloom evolution, including FRRF, Flavodoxin, sinking rates, TEPS, and supplement these with  $^{15}\text{N}$  and  $^{32}\text{Si}$  uptake rates;

- Additional methods are required to determine the role of the microbial community and zooplankton in the fate of POC and O<sub>2</sub> profiles of the upper ocean, community respiration, labelled particle decomposition experiments;
- Additional experiments are required for measuring export flux, such as trap calibration with thorium, large-volume pump thorium samples, more fluorometers for the upper trap moorings;
- Estimates of silica dissolution, bacterial production and respiration, and bacterial Fe-stress should occur;
- Measurements of micro- and meso-zooplankton grazing, and the prey (including particles) are desirable.

Thanks to the excellent presentations and spirited discussion from all participants, the workshop was very successful. The results of the workshop will be published as a PICES Scientific Report in 2004.