Report of Iron Fertilization Experiment Advisory Panel

The Advisory Panel on "An Iron Fertilization Experiment in the Subarctic Pacific Ocean" (IFEP) met in the evening of October 25. The IFEP Co-Chairman, Dr. Shigenobu Takeda, welcomed the members of the Panel and observers (see *Endnote 1*) and called the meeting to order. The agenda was reviewed and accepted without changes.

A 2-day IFEP planning workshop on "Iron fertilization experiment in the subarctic Pacific" was convened in Tsukuba prior to the PICES Ninth Annual Meeting (October 19-20, 2000). The objective of the workshop is to initiate planning for the experiment, including logistics, ships, and funding, etc. The workshop was very successful and thanks to 19 excellent presentations and the spirited discussions from the 36 participants (see *Endnote 2*).

Dr. Takeda introduced the schematic diagram of subarctic plankton ecosystem that includes new biological and geochemical processes reported during the workshop. He also listed similarity and differences in physical, chemical and biological characteristics between the eastern and western subarctic Pacific. Such differences have close relationship with the zonal gradients in atmospheric iron deposition.

From the results of the workshop, Dr. Harrison proposed a central hypothesis for the iron enrichment experiments in the subarctic Pacific. The hypothesis was adopted by IFEP after modification according to the suggestions and comments from Drs. K. Coale and P. Boyd, and other members (see *Endnote 3*). The experiment should be driven by scientific hypothesis and is to test the hypothesis on natural ecosystem and geochemical cycles, so that the word "iron fertilization" would be replaced as "iron enrichment".

IFEP recognizes that it is very important to have a close linking between the Canadian and Japanese program. It is considered that scientists and ships from both Canada and Japan should perform the eastern and western experiments as a collaborated program to make the east-west comparison stronger by using the same methodology and team. We also need the participation of American scientists and ships as well as scientists from other PICES countries to keep the international activity achieved during the workshop. Due to the number of scientists that are required to measure a wide variety of parameters, the experiment will require more than two ships. The R/V J.P. Tully (Fisheries and Ocean Canada) and R/V Kaiyo-Maru (Fisheries Agency Japan) or T/S Oshoro-Maru (Hokkaido University Japan) will be the base ships both in the eastern subarctic experiment in July/Aug 2002 (Stn. P) and in the western subarctic experiment in August 2003 (45-50°N, 160-165°E). The R/V Hakuho-Maru (University of Tokyo Japan) may be available to perform the survey for studying the long-term responses in October 2003. A preliminary experiment in the western subarctic in June-Aug is also planning to use the R/V Kaiyo-Maru.

The Panel also discussed the time line of proposals for research and ship time and the IFEP members from each country were requested to prepare requested information such as what they could measure/contribute to prepare the proposals as an international program. It will be distributed to colleagues who would be interested in participating.

IFEP recommends using a web site on the PICES home page to improve connections and communication between IFEP and other members (group of American scientists) who are proposing to participate the Canada-Japan experiments.

After the successful IFEP planning workshop, the IFEP felt strongly that the next step should be to convene a half-day mini-workshop or meeting at the PICES Tenth Annual Meeting in Victoria. This workshop would refine the experimental design of 2002 and 2003 in detail with information from preliminary experiment at the western subarctic Gyre in 2001 and Southern Ocean experiments in 2000-2001.

IFEP Endnote 1

Participation List

Canada
Paul J. Harrison
Maurice Levasseur

Japan
Isao Kudo
Kenshi Kuma
Hiroaki Saitoh
Sei-ichi Saitoh
Shigenobu Takeda
Atsushi Tsuda
Mitsuo Uematsu

Russia
Lev M. Gramm-Osipov

U.S.A.
Kenneth H. Coale
William P. Cochlan

Observer
Philip W. Boyd (U.K.)

IFEP Endnote 3

Proposed Experimental Summary

The North Pacific is characterized by relatively uniform distributions in temperature, salinity, macronutrients and light yet strong zonal gradients in atmospheric iron deposition exist between the eastern and western gyres. We hypothesize that

(1) The difference in episodic iron deposition gives rise to distinct phytoplankton communities that characterize these biogeochemical provinces.
(2) The biogeochemical response of any given province (air-sea flux of biogases, export flux of carbon) is driven by episodic events such as iron deposition.

To test these hypotheses (and offers as part of this program) an iron perturbation experiment, on the scale of the entire community is required such that the community response and resultant geochemical signal can be measured

Scientific questions

Fate/longevity of the bloom with an emphasis on ligand production and the response of the grazers (micro and mesozooplankton)

What is the magnitude and characteristics of particles (Carbon flux) sinking at the end of the bloom?

What is the production of various climate change biogases (DMS, N2O, methane, etc.) during and after the bloom?

IFEP Endnote 2

Report on IFEP Planning Workshop

Iron Fertilization Experiment Panel Planning Workshop
on
Designing the Iron Fertilization Experiment in the Subarctic Pacific

Tsukuba, Japan, October 19-20, 2000

Co-Conveners: C.S. Wong and S. Takeda
Co-Sponsor: The North Pacific Marine Science Organization (PICES)
Central Research Institute of Electric Power Industry (CRIEPI)

Specific objectives of the workshop:

- Establish the current knowledge about the role of iron in limiting phytoplankton production in the subarctic Pacific.
- Identify the specific questions that should be answered by the *in situ* iron fertilization experiment in the subarctic Pacific.
- Initiate planning for the experiment, including logistics and funding, etc.

Scientific Sessions

General overview of IronEx and SOIREE, iron chemistry and biology in seawater.
Physics in the North Pacific and Fe addition techniques
Biology in the North Pacific and IronEx
Chemistry in the North Pacific and IronEx

The workshop was very successful and thanks to 19 excellent presentations and the spirited discussions from the 36 participants.

What do we know from IronEX I andIronEX II and SOIREE, etc.

- Iron limitation is clearly present in populations of phytoplankton in HNLC regions.
- Iron enrichment de-couples larger phytoplankton from the meso-zooplankton community
- Evidence for carbon export in SOIREE is not clear. There may have been export of carbon, yet retention of iron. Evidence for carbon export in IronEX is clearer.
- Response in SOIREE was much slower than the response in IronEX.
- There is now more interest in the effect of iron enrichment in different macro-nutrient-limited regimes specifically low NO3 where N-fixation dominates N-uptake.
- Ship-based study of light limitation of iron enrichment in the SOIREE region showed that light limitation is present at 100 m.
- There is some interest in long-term addition experiments of low levels of iron.
- The role of meso-scale eddies is intriguing at Stn P. They may offer a way to track a patch of water for years, but the phytoplankton community in an eddy may be untypical of the G. of Alaska. Also eddies have no surface water expression and so their relevance to an iron enrichment experiment is not clear.
- The European community has just sent the Polarstern to the southern ocean (in the Atlantic sector) to do a SOIREE-type experiment over a longer time (CARUSO).

What do we still need to know?

- There is a need to study Stn. P, and NW Pacific, but other regions need to be studied as well.

- Fate of primary production (carbon): POC export flux, DOC, respiration and response of higher trophic levels (is there an increase in fish production?). The time scale is over a year, so the model approach is needed).
- What are the roles of ligands? What members of the community produce and take up ligands?
- Does zinc affect other enzyme processes?
- Need DMS/DMSP studies and other climate change biogases. Previous iron enrichment studies have measured DMS production. Should have both ships and aircraft for sampling. At Papa, ocean levels of DMS are very high. Atmospheric levels are low.
- We need to know the factors that influence the carbon-to-nutrient-and-other trace metal export ratios.
- Iron might end up below the mixed layer during long-term commercial projects. It might become available the next summer after winter mixing.
- Would long-term iron enrichment drive a system toward another limitation (N, Si, Zn, Co, etc)?
- What is the impact of long-term iron enrichment on fish? Governments may see the fish production as a secondary benefit of the iron enrichment, so this question will be asked of us. The public may see this as a problem, due to "wrong" species benefiting, such as pennate diatoms that produce domoic acid. (These are not questions that can be addressed with the current experiment)
- What are the chemical processes associated with iron saturation and super-saturation of seawater?
- How does Fe(II) stay around so long in Fe enrichment patches?
- What are the major grazers on diatoms and how they respond when diatom (pennate/centric) abundance increases?
- Understanding the dynamics of plankton ecosystem, export carbon flux and climate related gases to the iron enrichment is appropriate for the requests of Government and Industry who are seeking scientific information to asses the effect on future global atmospheric CO2 and environmental impacts.

What do we hope to learn from an iron enrichment experiment at Stn P and WSG?

- What are the similarities and differences in the plankton ecosystem response to iron fertilization in the subarctic Pacific? There is a special interest in the east-west North Pacific comparison which includes differences in dominant species (pennate/centric diatoms) and export flux (Org-C/Opal/CaCO3).

Summary of Canadian Program (extracted from the Canadian SOLAS Proposal)

- We are proposing to fertilize a 64 km2 patch of ocean near Stn P in the NE subarctic Pacific during July/Aug 2002. Iron will be added 3 or 4 times during the three week experiment and a wide variety of physical, chemical and biological parameters will be measured. In particular, we will carefully document the expected increase in phytoplankton biomass and the subsequent carbon flux out of the photic zone, the drawdown in CO2, and the production of other climate change gases such as DMS.

- There are several reasons why an iron enrichment experiment should be conducted at Stn P in the NE subarctic Pacific. Stn P or Ocean Station Papa (50 N and 145 W) has a 40 year time series of physical, chemical, and biological parameters and thus it has one of the longest open ocean time series in the world. Three large intensive sampling programs have provided detailed information, especially on biological rate process studies (SUPER, WOCE, and Canadian JGOFS). This large published data set/time series will provide an excellent background to assess the annual and interannual natural variability for evaluating the magnitude of the response to the iron addition experiment. The subarctic North Pacific represents a latitudinal gradient between the polar (Southern Ocean) and equatorial regions and therefore an iron addition experiment at Stn P will allow a comparison among the three large HNLC regions and between the eastern and western gyres in the subarctic Pacific.
- The subarctic NE Pacific has different physical, chemical and biological properties than the other two HNLC regions (Southern Ocean and Equatorial Pacific). In particular, it has a very shallow summer mixed layer depth, a strong, shallow pycnocline and low currents which should help to keep the iron patch intact and ensure the success of the experiment. The biodiversity of the plankton is different from the equatorial Pacific and Southern Ocean and therefore the response to the iron addition and the flux of carbon out of the photic zone may be different.

- Unlike the equatorial Pacific, Stn P is in close proximity (3 days steaming) to major research laboratories at the Institute of Ocean Sciences and the University of British Columbia and therefore it should be easier to document the longer term recovery from the iron addition. If the detailed documentation of the ecosystem response to a singe iron addition is successful, this will allow us to proceed to the next phase, repeated iron additions and the longer term monitoring that this will require.
- **Key questions that have not been entirely resolved by previous iron enrichment experiments, are:**
  1) How does the change in biodiversity and foodweb structure differ for markedly different ecosystems which have been perturbed by an iron additon?
  2) What is the drawdown of CO_2 and especially the flux of carbon to the deep ocean?
  3) How does the production of ligands influence the iron chemistry and the longevity of the phytoplankton bloom?
  4) How does zooplankton grazing influence the formation of the bloom and the carbon flux (e.g. fecal pellet production),
  5) What is the long term response and recovery of the ecosystem following an iron addition?
  6) What is the magnitude of production of other climate change gases such as DMS during the bloom and how is the production influenced by phytoplankton species, microbial processes and grazing?

Objectives

1) To measure the response of bacteria, phytoplankton and zooplankton in terms of species, standing stocks and rate processes to the iron addition.
2) To measure the drawdown of CO_2 and the flux of carbon to depth.
3) To study the relationship between ligand production and the associated changes in the iron chemistry and their influence on the longevity of the phytoplankton bloom.
4) To assess the influence of zooplankton grazing on the phytoplankton bloom formation and carbon flux.
5) To follow the long term response and recovery of the phytoplankton bloom.
6) To quantify the production of various climate change gases during the iron enrichment experiment and assess the factors which influence the production of these biogases.

- **Biological Oceanographic sampling**

The upper 150 m will be sampled vertically (6-8 depths) each day using 12 acid-cleaned PVC samplers on a CTD/water sampler rosette system at the patch center (determined by SF_6 levels) and in the surrounding waters.

Real-time vertical profiling of temperature, salinity, transmissivity, chlorophyll a fluorescence and underwater irradiance (PAR, 400-700 nm) will be carried out. Discrete water samples will be analysed for:

- chlorophyll *a* (size-fractionated, >20, 5-20, 2-5 and 0.2-2 µm),
- heterotrophic bacterial abundance
- microzooplankton abundance
- phytoplankton abundance (flow cytometry, epifluorescence and light microscopy).

Additional samples will be incubated on deck to measure rates of:

- primary production (14C, 24 h incubation, simulated in situ and size-fractionated as for chlorophyll a,
- bacterial production
- microzooplankton grazing

Mesozooplankton abundance will be assessed from 150-0 m vertical hauls. The Th:U activity ratio of particles in the upper water column will be collected using a submersible pumping system.

- **Geochemical measurements**

Two types of sampling will be done: hydrocasts and underway sampling from the vessel's non-toxic seawater supply (intake 5 m subsurface) and analysed by fluorometry (calibrated with discrete chlorophyll a samples every 2 d, corrected for quenching during daylight hours), and using a bubble-segmented automated nutrient analysis system, respectively. Underway samples for dissolved iron will be conducted from a clean towed batfish sampling system, and samples for pCO_2 will be drawn from the vessel's non-toxic seawater system. Phytoplankton samples for the single-cell flavodoxin assay will be pre-concentrated onboard ship and later analysed shoreside.

Sampling will be conducted by:

(1) Towed batfish: Continuous sampling will be made from a towed batfish with a clean pump and tubing for the following measurements (This is not a pumping undulating fish):
    (a) Conductivity/salinity sensor
    (b) SF6
    (c) fCO2, pH
    (d) nitrate
    (e) iron
    (f) chlorophyll-a (fluorometer)
(2) Hydrocasts by rosette CTD/Niskin samplers
    (a) T, S
    (b) O2
    (c) Chlorophyll-a
    (d) Macro-nutrients (N, P, Si) by auto-analyzer
    (e) Iron by chemiluminescence
    (f) Particulate iron size-fractions, total iron, dissolved iron
    (g) SF6
    (h) DIC, TA, pH
    (i) DOC, DON, POC
    (j) DMS
(3) Free-drifting sediment traps (at 50 m intervals, 50-600 m) deployed and retrieved at 3 day intervals to obtain samples for detritus organic C, N, P, Si, PIC, Fe, Cd, Al, rare earth elements, Th/U ratios, coccolithophore counts, and planktonic species, and scanning electron microscope pictures.

- Deckboard perturbation experiments

Algal carbon, growth rates and C:chl *a* ratios, etc.

- We (Drs. Wong and Harrison) hope to have one or two strings of moored sediment traps, plus free floating traps. Moored traps would be at the control site. Floating traps would hopefully follow the patch. It will be difficult to keep the patch and traps together, but there is a real need for trap data to try to quantify and characterize export. Free-floating sediment traps may perform differently than moored traps. Therefore we should have free-floating traps in and out of the Fe patch.
- Need to know more about micro-zooplankton.
- Want to know effects of ligands, and also climate change biogases, including but not limited to DMS, CO2, N2O. SOIREE showed enhancement of nitrous oxide at the top of the thermocline, so this is one gas that should be studied.
- There will be aircraft-based sampling of gases and aerosols above the Fe patch.
- Hope to sample over a longer time, possibly by back-to-back cruises extending over 6 weeks. Expect to have *J.P. Tully* for four weeks. Will need another ship for one of these two cruises. Cruises could be separated by several weeks if patch could be found on second cruise.
- Iron limitation at Stn P in July to August is severe, so project will be then.
- Project will be part of the Canadian SOLAS project.

Summary of Japanese programs

- Proposing preliminary experiment in Jun-Aug 2001 in NW Pacific in Western Subarctic Gyre, with next effort in Aug-Sept 2003.
- When: 2001 about 40 days during June-August (Kaiyo-maru)
  2003, (1) August-mid September (Oshoro-maru or Kaiyo-maru)
  Initiation of SF6/Fe patch, Basic study
  (2) October (Hakuho-maru)
  Intensive sampling and measurements and long-term responses
- **Where:** Western Subarctic Gyre: 45-50^{o}N, 160-165^{o}E

- **Why:**
  1. To measure the response of bacteria, phytoplankton and zooplankton in terms of species, standing stocks and rate processes to the iron addition.
  2. To measure the drawdown of CO2 and the flux of carbon export.
  3. To study the interaction between biogeochemical processes in the surface water during the phytoplankton bloom and the production of climate gases in the atmosphere.
  4. To study the relationship between phytoplankton (diatom) production and the higher trophic level (salmon).
  5. To assess the influence of iron supply on the characteristics of the plankton ecosystem in the western subarctic Pacific.
- **Proposal:**
  The Science and Technology Agency (Kasinchouhi: 2001-2005)
  Ministry of Education, Science and Culture (Kakenhi: 2001 Basic Science, 2002-2004 Scientific project with high priority)
  NEDO grant

- Japan SOLAS is still in the preparation stage. A study of the influence of natural atmospheric iron supply on the characteristics of the plankton ecosystem in the western subarctic Pacific will be one of the important topics. (Long cruise staying at a station in Spring high dust season).

Kenneth Coale's summary of next US effort in iron enrichment experiment, SOFEX

- Will be along 170 west, near SOJGOFS site.
- Will use SeaSoar type of device that pumps water to ship.
- SOJGOFS found jump in silicate at Polar front near 62S, with increase south of front. SOFEX will do experiments N and S of front, to see which type of species is enhanced in each region (*Phaeocystis* and diatoms).
- Big complement of scientists and studies. There are ten more scientists than berths on ship. Lack of ship bunks is a general problem in iron enrichment cruises. For example, samples will be frozen for later analysis by Edie Rue and will run the only ligand study.
- They will need to find the northern patch after a week or more, and plan to use lagrangian drifters to keep track of the patch.

Methodology

- Need to standardize sampling methods to enable comparison among experiments in different HNLC regions. List of dominant species and their biomass is useful for the comparison. Export production is difficult to get quantitative samples?
- First step is the application of previous IronEx methodology (FeSO4, initial concentration level, Fe infusion timing, etc) and then we may go to new method such as the use of chelated iron (iron lignite), long-period and low-level iron supply, etc.
- Should add DMSP to list of samples.
- Micro-zooplankton are important grazers and dilution experiments are necessary to quantify coupling of primary production and grazing.
- Fe organic ligand study has technical problems.
- Analyses of biogases in the atmosphere are important, but how?
- Bag experiments have limitations. Small bags might not represent the ocean. Large bags are too difficult to manage. However there should be some role for bag experiments.
- Use of organic chelated iron (iron lignite) may provide carbon source for heterotrophic organisms.
- Stable isotope study will be done in SOFEX to see the proxy of paleo-oceanographic environment.
- After silicate in surface water will be used up, a re-infusion of Fe will give us some idea of the long-term change in dominant species.

Logistics

- The Stn P project needs a second ship. Kenneth Coale recommended that a U.S. ship may be available if a group of American scientists were to propose to participate. The US SOLAS program would be one way to generate support. It would help to have a Canadian-Japanese proposal ready. US scientists must start to prepare proposals now for Stn P 2002 cruise.

- A Canadian or US airplane would be useful for tracking the Fe patch. An airplane with a hyperspectral sensor would be really useful.
- ADIOS-2 will be launched soon. It will be useful (similar to SEAWIFS).