Canadian SOLAS/PICES-IFEP session on "*Response of the upper ocean to meso-scale iron enrichment*"

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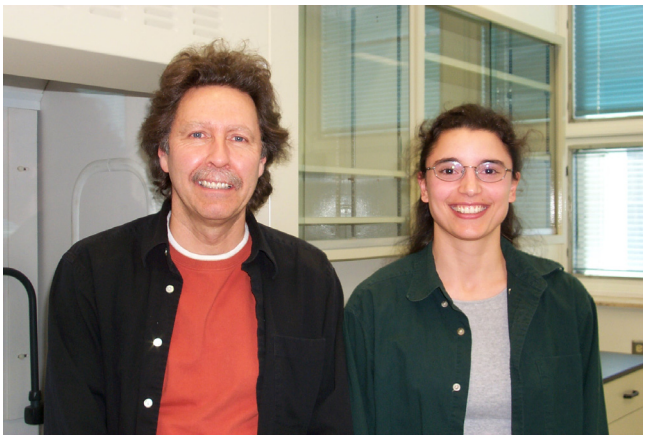

Dr. Maurice Levasseur is a professor in the Department of Biology at Université Lava, where he leads the Canadian Chair on Climate Variability and Plankton Ecosystems. He is also the Chairman of the Canadian SOLAS Network (csolas.dal.ca). His research focuses on the marine production of the climatically-active gases and the eco-physiology of harmful algal blooms. Within PICES, Maurice has been involved in activities of the Advisory Panel on Iron Fertilization Experiment *and the Working Group on* Ecology of the Harmful Algal Blooms in the North Pacific.

Anissa Merzouk graduated with a B.Sc. in Marine Biology from the Université du Québec à Rimouski. She is currently completing a Ph.D. in Oceanography at Université Laval under the supervision of Prof. Levasseur, working on understanding the controls of the biological production and consumption of DMSP and DMS in surface waters. Within the C-SOLAS program, she participated in the SERIES iron enrichment experiment in the NE Pacific to determine the influence of iron on the distribution and biological cycling of DMSP and DMS.

Background

The productivity of large portions of the global ocean is thought to be limited by the availability of iron, a micronutrient essential to phytoplankton growth. So far, eight meso-scale iron fertilization experiments have been conducted in order to test this hypothesis, and to provide insights on the potential effect of iron addition on algal blooms development and the biogeochemical cycle of major elements, with a special focus on climatically-active gases, such as CO_2 and dimethylsulfide (DMS). Two of these recent experiments conducted in the North Pacific were developed under the umbrella of PICES, through its Advisory Panel on *Iron Fertilisation Experiment*, co-chaired by Drs. Shigenobu Takeda and C.S. Wong. These experiments took place in 2001 in the Northwest Pacific (SEEDS), and in 2002 in the Northeast Pacific (SERIES). Both experiments were successful and generated important new findings (Tsuda *et al.* 2003. A mesoscale iron enrichment in the western subarctic Pacific induces large centric diatom bloom. Science, 300: 958-961; Boyd *et al.* 2004. Evolution, decline and fate of an iron-induced subarctic phytoplankton bloom. Nature, 428: 549-553).

Meso-scale experiments are costly, involve many scientists and generate huge volumes of data. It is our responsibility to maximize the diffusion of this information and to ensure a skilful utilization of these unique data sets. A group of research scientists involved in the planning and realization of these experiments thought that the timing was good to synthesize and compare the responses obtained so far during these experiments. To accomplish this task a joint C-SOLAS/PICES-IFEP session on "*Response of the upper ocean to meso-scale iron enrichment*" was convened on February 17-18, during the ASLO/TOS 2004 Ocean Research Conference held in Honolulu, Hawaii (session organizers: Maurice Levasseur, Atsushi Tsuda, William Miller, William Cochlan and Richard Rivkin).

The call for papers was very well received, resulting in a session composed of 23 oral presentations and 17 posters. As expected, the session was a showcase for the most recent experiment: SERIES. But there was also significant contribution from SEEDS and SOFeX, and some presentations proposed thoughtful inter-comparisons between the various meso-scale experiments. This special session allowed to recognize the similarities and differences in the responses obtained from these experiments.

Overview of presentations

The session started with a tutorial by Kenneth Coale who presented a synthesis of the knowledge gained from the seven mesoscale iron enrichments experiments conducted so far, pointing at similarities but also emphasizing that each experiment was unique in terms of location, season and initial conditions, and thus generated different responses to iron enrichment. The take home message was that although we know much more than 10 years ago, much remains to be understood in order to properly

evaluate the global impact of iron on ocean biogeochemical cycles and climate.

The tutorial was followed by 4 talks on SOFeX, highlighting new outcomes from this expedition in the Southern Ocean. William Cochlan showed that there was a clear change in the relative utilization of new and re-generated nitrogen following the iron fertilization, with nitrate uptake increasing by 15-fold and 25-fold north and south of the Antarctic Polar Front Zone (APFZ), respectively. Stephen Baines reported on iron-induced changes in the elemental stoichiometries of individual diatoms and flagellates using a synchrotron x-ray fluorescence microprobe. His results indicate biochemical changes in the resident plankton, suggesting differences in the biogeochemistry of Fe-replete and Fe-deplete regions of the ocean. Mark Brzezinski showed that iron fertilization caused a shift from non-Redfield to Redfield nutrient uptake ratios in the Southern Ocean, shifts that will have strong implications for elemental cycling and climate during periods of enhanced Fe supply. Finally, Michael Hiscock demonstrated that iron addition resulted in an increase in the maximum quantum yield of photosynthesis, but that the intensity of the response varied within size fractions between the nitrate-rich and silicate-rich in the waters north and south of the APFZ. These presentations, along with the companion posters, highlighted important regional variability in the responses of the plankton community to iron fertilization in the Southern Ocean.

The next 2 talks, accompanied by 4 posters, reported more specifically on the SEEDS expedition conducted in the NW Pacific in 2001. Atsushi Tsuda gave an overview of SEEDS where the iron fertilization induced a large centric diatom bloom resulting in a marked consumption of macronutrients, a huge increase (factor ~ 20) in chlorophyll *a* concentrations and a marked drawdown in pCO_2. By day 13 of the experiment, the export of fixed carbon represented only 13% of the primary production in the iron-enriched patch, with most of POC (particular organic carbon) remaining in the surface mixed layer. The fate of the bloom remains unknown. Isao Kudo presented interesting results on the effect of water temperature on the response of the phytoplankton community to iron addition obtained in shipboard experiments performed during SEEDS and SERIES. The phytoplankton growth rate in the fraction of >10 μm was higher in the NW Pacific than in the NE Pacific for similar iron addition and temperature (12°C). Since surface temperature increased from 5 to 9°C in the weeks before the SEEDS experiment, he hypothesized that the growth rate dependence on temperature could explain the exceptionally large increase in chlorophyll *a* and primary production measured during SEEDS. Jun Nishioka presented a poster on the distribution of size-fractionated iron and showed that iron supply is higher in the NW Pacific than in the NE Pacific due to more frequent atmospheric inputs. During SEEDS, the added dissolved iron was rapidly transformed to labile particulate iron, reducing its bio-availability to phytoplankton, a process that probably also occurs for dissolved iron originating from atmospheric inputs. In his poster, Takeshi Yoshimura demonstrated that in the NW Pacific, 10 to 20% of the net organic carbon production was converted to DOC (dissolved organic carbon) during the growth and stationary phases of the bloom. In the NE Pacific, the net DOC production was higher during the decline phase of the bloom, suggesting the domination of decomposition processes. Hiroaki Saito's poster suggested that phytoplankton growth exceeded micro-zooplankton grazing at the beginning of the SEEDS experiment, but micro-zooplankton grazing rates and phytoplankton grazing mortality increased rapidly at the end of the experiment. These results highlighted the balance between phytoplankton growth and loss due to grazing, and how this equilibrium may be affected by iron. Naoki Yoshie presented a poster on the modeling of the SEEDS diatom bloom. The model successfully reproduced the vertical distributions of macronutrients and chlorophyll during the evolution of the bloom. The model predicts that the effect of iron on the ecosystem would last for 40 days, and that the export flux during the 13-day observation period represents 20 to 30% of the export predicted for 40 days.

The following 15 oral presentations (with 5 posters) reported on SERIES, the most recent meso-scale iron enrichment experiment at that time. This block of talks began with an overview of SERIES by Phillip Boyd, who presented the evolution, decline and fate of the SERIES bloom. His talk was completed by the presentation of David Timothy on the nutrient dynamics, uptake and export of carbon and biogenic silica. Their results showed that the termination of the diatom bloom was due to iron limitation followed by silicic acid limitation. More than half of the carbon fixed by the bloom was grazed or re-mineralized by bacteria and only a small portion of the bloom's particulate carbon (18%) and biogenic silica (34%) was exported from surface waters (>50 m). Jean-Eric Tremblay presented data on phytoplankton growth and nutrient uptake ratios during the evolution of the bloom. The nano-phytoplankton bloom was initiated by increased growth rates immediately after iron addition, and was halted by grazing losses. A presentation by Nelson Sherry and a poster by Paul Harrison described the shift in phytoplankton community composition from small nano-phytoplankton (flagellates) to large pennate diatoms. Chlorophyll *a* and primary production increased rapidly during the diatom bloom in parallel with a drawdown of macronutrients. Adrian Marchetti presented field and lab data on elemental composition ratios in a diatom, showing that iron-limitation resulted in an increase of the Si/N ratio due to a decrease in N-uptake. He concluded that diatoms were iron-stressed before the full depletion of silicic acid during SERIES.

Richard Rivkin presented an insightful synthesis of the influence of iron on bacterial stocks and processes during different meso-scale iron enrichments. Iron increased bacterial abundance and production during all fertilization experiments. The bacterial response during SERIES was markedly larger than in the Equatorial Pacific (IronEx II) and Southern Ocean (SOIREE), resulting in increased retention of carbon in the surface layer and reduced export to the deep ocean. Carol Adly and Michelle Hale presented posters on the bacterial response to iron enrichment. The first author reported a small but rapid increase in bacterial abundance and production immediately (few hours) after iron enrichment, suggesting that bacteria were initially iron-limited. Hale's results showed that the bacteria were generally DOM-limited during the first days of the experiment. Bacterial production and growth rates peaked 6 days prior to the increase in biomass, suggesting that bacteria were under strong grazing pressure during the first 13 days of the bloom.

Sonia Michaud and Michel Scarratt presented results on the influence of iron on the dimethylsulfoniopropionate (DMSP) and dimethylsulfide (DMS) distribution during SERIES, and Anissa Merzouk presented data on DMSP and DMS biological cycling. The bacterial utilization of DMSP shifted from high DMS production in the sulfur-rich nano-phytoplankton bloom to low DMS production during the sulfur-poor diatom bloom, resulting in an overall DMS deficit in the iron-enriched patch. It is the first time that a negative effect of iron fertilization on DMS is observed. William Miller and Rene-Christian Bouillon showed that iron fertilization decreased the DMS photo-oxidation rate coefficient. They proposed that nitrate-photolysis played a significant role in DMS photo-degradation. Yvonnick. Le Clainche used an inverse modeling approach to show that the regional increase in DMS concentrations during SERIES resulted from a combination of low ventilation and high DMS biological net production.

Robert Moore presented data on the production and fluxes of isoprene and methyl-iodide, two atmospherically-reactive gases. The net production of isoprene and its flux to the atmosphere increased during the course of the experiment, whereas methyl-iodide concentrations were lower in-patch than out-patch. These gases were of biogenic origin but their production mechanisms are poorly understood.

Kenneth Denman presented the modeling of the plankton community structure during the iron enrichment. The model reproduced well the development of the bloom but not the export of carbon fixed by the diatom bloom, suggesting that processes such as aggregation may have played a role in increasing the export flux at the end of the bloom.

Less usual for an ASLO meeting, the last two talks reported on the influence of iron fertilization on the atmospheric distribution of DMS, methane sulfonic acid (MSA) and aerosols. Moire Wadleigh presented the sea-to-air DMS fluxes and atmospheric DMS concentrations, while Lisa Phinney reported on aerosol processing over the region of the SERIES experiment. DMS fluxes were correlated with seawater DMS concentrations and wind speeds. Atmospheric DMS, MSA and sulfate concentrations were high in the study area compared to mean worldwide values. DMS and its degradation products were particularly elevated during a regional episode of high seawater DMS concentrations around days 6-9.

Conclusions

Papers presented during the session revealed important similarities and differences in the responses to iron fertilization observed in the different high nutrient low chlorophyll (HNLC) oceanic regions. One noteworthy similarity is that the growth of phytoplankton from all size classes seemed to be stimulated by iron addition, with small flagellated cells blooming first, followed by the diatoms.

Although a decrease in pCO_2 is generally measured in those experiments, results from SERIES indicate a low carbon sequestration efficiency. Whether such low efficiency can be extrapolated to the other HNLC regions is uncertain since bloom termination was generally not monitored during previous experiments. Carbon sequestration may vary depending on the structure of the phytoplankton assemblage, the limiting nutrient (Fe, nitrate, silicate), grazing, respiration, *etc*. Since these conditions vary from one site to another, the efficiency of carbon sequestration is expected to change as well. There is thus a need to determine the fate of the bloom in the major HNLC regions.

In addition to altering the carbon cycle, iron fertilization may also affect the production of other climatically-active biogenic gases such as DMS. During SERIES, the iron-induced diatom bloom coincided with a decrease in DMS concentrations. This was a clear departure from previous experiments where iron addition resulted in an increase in DMS. Again, these conflicting results call for further experiments. In order to properly evaluate the global impact of iron on sea-to-air exchange of climatically-active gases, we need a minimum, but statistically sound, understanding of the sensitivity of the different HNLC regions to iron. This can only be achieved through repeated, well planned, experiments. Given that up to 40% of the ocean surface is limited by iron, these experiments are essential steps in our quest to understand past, present, and future climate.