



Editorial

Introduction to Subarctic iron Enrichment for Ecosystem Dynamics Study II (SEEDS II)

Science is facts. Just as houses are made of stones, so is science made of facts. But a pile of stones is not a house and a collection of facts is not necessarily science.

Henri Poincare

The role of the ocean in regulating climate change is now recognized as being of critical importance. Surface Ocean–Lower Atmosphere Study (SOLAS) is an international research initiative that has as its goal: “To achieve quantitative understanding of the key biogeochemical–physical interactions and feedback between the ocean and the atmosphere, and how this coupled system affects and is affected by climate and environmental change.”

Testing hypotheses such as feedback between ocean ecosystems and climate requires large and coordinated field campaigns. Subarctic iron Enrichment for Ecosystem Dynamics Study (SEEDS) in the summer of 2001 was the first mesoscale iron-enrichment study in the subarctic Pacific to test the iron-limitation hypothesis (Tsuda et al., 2003). Subarctic Ecosystem Response to Iron Enrichment Study (SERIES) was carried out in the eastern subarctic gyre of the North Pacific in 2002 by the Canadian and Japanese SOLAS groups, when they conducted a 26-day study of the iron patch (Boyd et al., 2004). Three years after SEEDS, SEEDS II was conducted by two research vessels, R/V *Hakuho Maru* and R/V *Kilo Moana* for an intensive longer period as a result of the international collaboration among Japan, Canada, and United States scientists in the summer of 2004. For the SEEDS II experiment, several groups of atmospheric scientists and specialists of trace gases in seawater joined the original SEEDS group of skilled marine scientists and conducted research in the lower atmosphere. All three experiments resulted from the international collaborative field project developed under the umbrella of North Pacific Marine Science Organization (PICES), through its Advisory Panel on the Iron Fertilization Experiment in the Subarctic Pacific Ocean (IFEP). IFEP was approved by PICES in 1998 and science plans and the coordination of various experiments were discussed and planned through workshops and meetings (Takeda and Wong, 2006).

During the SEEDS II experiment, the iron patch was traced for 26 days, which included observations on the development and decline of the bloom by mapping with sulphur hexafluoride (Tsumune et al., 2009). The experiment was made at almost the same location and the same season as SEEDS. However, the results were very different between SEEDS and SEEDS II. During SEEDS, a high accumulation of surface phytoplankton biomass ($\sim 18 \text{ mg chl m}^{-3}$) was accompanied by a floristic shift from oceanic diatoms to neritic diatoms (Tsuda et al., 2003), which

was the highest chlorophyll-*a* concentration among all of the iron fertilization experiments in the world ocean (de Baar et al., 2005; Boyd et al., 2007). In contrast, during SEEDS II, the surface chlorophyll-*a* accumulation was lower, $0.8\text{--}2.5 \text{ mg m}^{-3}$, and with no prominent diatom bloom (Tsuda et al., 2007). Photosynthetic competence in terms of Fv/Fm for the total phytoplankton community in the surface waters increased after the iron enrichments, accompanied by an increase in primary production, and then it returned to the ambient level by day 20 (Kudo et al., 2009; Suzuki et al., 2009). These results suggest that the photosynthetic physiology of the phytoplankton assemblage was improved by the iron enrichments and returned to an iron-stressed condition during the declining phase of the bloom. Pico-phytoplankton ($< 2 \mu\text{m}$) became dominant in the chlorophyll-*a* size distribution after the bloom (Sato et al., 2009). We observed a nitrate drawdown of $3.8 \mu\text{M}$ in the patch (day 21), but there was no difference in the silicic acid concentration between the patch and outside the patch (Saito et al., 2009). We also observed a significant increase of particle flux in the patch (Aramaki et al., 2009). Mesozooplankton (copepod) biomass, which was dominated by the ontogenetic vertical migrator *Neocalanus plumchrus*, was 3–5 times higher during the bloom development phase in SEEDS II compared to SEEDS. The copepod biomass increased exponentially. The grazing rate estimation indicates that the copepod grazing prevented the formation of an extensive diatom bloom that was observed in SEEDS and led to the change to a pico-phytoplankton-dominated community towards the end of the experiment (Tsuda et al., 2009; Saito et al., 2009).

Activities in atmospheric chemistry and the chemistry of trace gases in the seawater were an important component of SEEDS II. Although we observed a significant increase in CH_3Br in the patch, other trace gases did not increase (Hashimoto et al., 2009). We observed a significant increase in DMSP in the patch, but the DMS concentration was not statistically different between the patch and out-patch (Nagao et al., 2009). Moreover, the iron addition affected the bacterial cycling of the DMS-related chemicals in the patch (Lizotte et al., 2009).

The following 19 papers in this special issue were the outcome of the SEEDS II campaign. The disciplinary scope of the papers is very broad, not only linking chemical, physical and biological oceanography, but atmospheric chemistry and physics. This is a rather unique combination of fields to publish their results in Deep-Sea Research—Part II and we hope that this special issue will be popular with the atmospheric science community. There are several publications outside of this volume on iron and trace metal chemistry (Kondo et al., 2008; Nakatsuka et al.,

2007; Nishioka et al., 2007; Sato et al., 2007) methane dynamics (Sasakawa et al., 2008), alkane dynamics (Kameyama et al., 2009), the chemistry of suspended particles (Iwamoto et al., 2009), and some papers are still in preparation.

We thank the captains and crews of the R/Vs *Hakuho Maru* and *Kilo Moana*, and our colleagues onboard during the cruises. Prof. Paul Harrison gave us valuable advice and continuous encouragement throughout our study. This campaign has contributed to the international activities of SOLAS, IMBER, IGAC, and PICES.

References

- Aramaki, T., Nojiri, Y., Imai, K., Otsuka, S., 2009. Behavior of particulate materials during iron fertilization experiments in the western subarctic Pacific (SEEDS and SEEDS II) 56 (26), 2875–2888.
- Boyd, P.W., Law, C.S., Wong, C.S., Nojiri, Y., Tsuda, A., Lavasseur, M., Takeda, S., Rivkin, R., Harrison, P.J., Strzpek, R., Gower, J., McKay, R.M., Abraham, E., Arychuk, M., Barwell-Clarke, J., Crawford, W., Crawford, D., Hale, M., Harada, K., Johnson, K., Kiyosawa, H., Kudo, I., Marchetti, A., Miller, W., Needoba, J., Nishioka, J., Ogawa, H., Page, J., Robert, M., Saito, H., Sastri, A., Sherry, N., Soutar, T., Sutherland, N., Taira, Y., Whitney, F., Wong, S.-K.E., Yoshimura, T., 2004. The decline and fate of an iron-induced subarctic phytoplankton bloom. *Nature* 428, 549–553.
- Boyd, P.W., Jickells, T., Law, C.S., Blain, S., Boyle, E.A., Buesseler, K.O., Coale, K.H., Cullen, J.J., de Baar, H.J.W., Follows, M., Harvey, M., Lancelot, C., Lavasseur, M., Owens, N.P.J., Pollard, R., Rivkin, R.B., Sarmiento, J., Schoemann, V., Smetacek, V., Takeda, S., Tsuda, A., Turner, S., Watson, A.J., 2007. Mesoscale iron enrichment experiments 1993–2005: synthesis and future direction. *Science* 315, 612–617.
- de Baar, H., Boyd, P.W., Coale, K.H., Landry, M.R., Tsuda, A., Assmy, P., Bakker, D.C.E., Bozec, Y., Barber, R.T., Brzezinski, M.A., Buesseler, K.O., Boyé, M., Croot, P.L., Gervais, F., Gorbunov, M.Y., Harrison, P.J., Hiscock, W.T., Laan, P., Lancelot, C., Law, C.S., Lavasseur, M., Marchetti, A., Millero, F.J., Nishioka, J., Nojiri, Y., van Oijen, T., Riebesell, U., Rijkenberg, M.J.A., Saito, H., Takeda, S., Timmermans, K.R., Veldhuis, M.J.W., Waita, A.M., Wong, C.-S., 2005. Synthesis of iron fertilization experiments: from the iron age in the age of enlightenment. *Journal of Geophysical Research* 110, C09S16, doi:10.1029/2004JC002601.
- Hashimoto, S., Toda, S., Narita, Y., Kurihara, K.M., Akatsuka, Y., Oda, H., Nagai, T., Nagao, I., Kato, S., Kudo, I., Suzuki, K., Uematsu, M., 2009. Production and air-sea flux of halomethanes in the western subarctic Pacific in relation to phytoplankton pigment concentrations during iron fertilization experiment (SEEDS II). *Deep-Sea Research II* 56 (26), 2928–2935.
- Iwamoto, Y., Narita, Y., Tsuda, A., Uematsu, M., 2009. Single particle analysis of oceanic suspended matter during the SEEDS II iron fertilization experiment. *Marine Chemistry* 113, 212–218.
- Kameyama, S., Tsunogai, U., Nakagawa, F., Sasakawa, M., Komatsu, D.D., Ijiri, A., Yamaguchi, J., Horiguchi, T., Kawamura, H., Yamaguchi, A., Tsuda, A., 2009. Enrichment of alkanes within a phytoplankton bloom during an in situ iron enrichment experiment (SEEDS II) in the western subarctic Pacific. *Marine Chemistry* 115 (1–2), 92–101.
- Kondo, Y., Takeda, S., Nishioka, J., Obata, H., Furuya, K., Johnson, W.K., Wong, C.S., 2008. Organic iron (III) complexing ligands during an iron enrichment experiment in the western subarctic North Pacific. *Geophysical Research Letters* 35, L12601, doi:10.1029/2008GL033354.
- Kudo, I., Noiri, Y., Cochlan, W.P., Suzuki, K., Aramaki, T., Ono, T., Nojiri, Y., 2009. Primary productivity, bacterial productivity and nitrogen uptake in response to iron enrichment during the SEEDS II. *Deep-Sea Research II* 56 (26), 2755–2766.
- Lizotte, M., Lavasseur, M., Kudo, I., Suzuki, K., Tsuda, A., Kiene, R.P., Scarratt, M.G., 2009. Iron-induced alterations of bacterial DMSP metabolism in the western subarctic Pacific during SEEDS-II. *Deep-Sea Research II* 56 (26), 2889–2898.
- Nakatsuka, S., Sohjin, Y., Norisuye, K., Okamura, K., Takeda, S., Nishioka, J., 2007. Physicochemical speciation of trace metals during the mesoscale iron enrichment (SEEDS II) in the western North Pacific. *Geochimica et Cosmochimica Acta* 71 (15), A704 (Suppl. S).
- Nagao, I., Hashimoto, S., Suzuki, K., Toda, S., Narita, Y., Tsuda, A., Saito, H., Kudo, I., Kato, S., Kajii, Y., Uematsu, M., 2009. Responses of DMS in the seawater and atmosphere to iron enrichment in the subarctic western North Pacific (SEEDS-II). *Deep-Sea Research II* 56 (26), 2899–2917.
- Nishioka, J., Ono, T., Saito, H., Nakatsuka, T., Takeda, S., Yoshimura, T., Suzuki, K., Kuma, K., Nakabayashi, S., Tsuda, A., 2007. Iron supply to the western subarctic Pacific: importance of iron export from the Sea of Okhotsk. *Journal of Geophysical Research* 112, C10012, doi:10.1029/2006JC004055.
- Saito, H., Tsuda, A., Nojiri, Y., Aramaki, T., Ogawa, H., Yoshimura, T., Imai, K., Kudo, I., Nishioka, J., Ono, T., Suzuki, K., Takeda, S., 2009. Biogeochemical cycling of N and Si during the mesoscale iron-enrichment experiment in the western subarctic Pacific (SEEDS-II). *Deep-Sea Research II* 56 (26), 2745–2754.
- Sasakawa, M., Tsunogai, U., Kameyama, S., Nakagawa, F., Nojiri, Y., Tsuda, A., 2008. Carbon isotopic characterization for the origin of excess methane in subsurface seawater. *Journal of Geophysical Research* 113, C03012, doi:10.1029/2007JC004217.
- Sato, M., Takeda, S., Furuya, K., 2007. Iron regeneration and organic iron (III)-binding ligand production during in situ zooplankton grazing experiment. *Marine Chemistry* 106, 471–488.
- Sato, M., Takeda, S., Furuya, K., 2009. Responses of pico- and nanophytoplankton to artificial iron infusions observed during the second iron enrichment experiment in the western subarctic Pacific (SEEDS II). *Deep-Sea Research II* 56 (26), 2745–2754.
- Suzuki, K., Saito, H., Isada, T., Hattori, A., McKay, R.M.L., Kiyosawa, H., Kuwata, A., Kawanobe, K., Tsuda, A., 2009. Community structure and photosynthetic physiology of phytoplankton in the northwest subarctic Pacific during an in situ iron fertilization experiment (SEEDS II). *Deep-Sea Research II* 56 (26), 2733–2744.
- Takeda, S., Wong, C.S., 2006. Report of the 2004 Workshop on In Situ Iron Enrichment Experiments in the Eastern and Western Subarctic Pacific. PICES Scientific Report no.31, pp. 188.
- Tsuda, A., Takeda, S., Saito, H., Nishioka, J., Kudo, I., Nojiri, Y., Suzuki, K., Uematsu, M., Wells, M.L., Tsumune, D., Yoshimura, T., Aono, T., Aramaki, Y., Cochlan, W.P., Hayakawa, M., Imai, K., Isada, T., Iwamoto, Y., Johnson, W.K., Kameyama, S., Kato, S., Kiyosawa, H., Kondo, Y., Lavasseur, M., Machida, R., Nagao, I., Nakagawa, F., Nakanishi, T., Nakatsuka, S., Noiri, Y., Obata, H., Oguma, K., Ono, T., Sakuragi, T., Sasakawa, M., Sato, M., Shimamoto, A., Takada, H., Trick, C.G., Watanabe, Y.Y., Wong, C.S., Yoshie, N., 2007. Evidence for the grazing hypothesis: grazing reduces phytoplankton responses of the HNLC ecosystem to iron enrichment in the western subarctic Pacific (SEEDS II). *Journal of Oceanography* 63, 983–994.
- Tsuda, A., Takeda, S., Saito, H., Nishioka, J., Nojiri, Y., Kudo, I., Kiyosawa, H., Shiimoto, A., Imai, I., Ono, T., Shimamoto, A., Tsumune, D., Yoshimura, T., Aono, T., Hinuma, A., Kinugasa, M., Suzuki, K., Sohrin, Y., Noiri, Y., Tani, H., Deguchi, Y., Tsurushima, N., Ogawa, H., Fukami, K., Kuma, K., Saino, T., 2003. A mesoscale iron enrichment in the western subarctic Pacific induces large centric diatom bloom. *Science* 300, 958–961.
- Tsuda, A., Saito, H., Machida, R., Shimode, S., 2009. Meso- and microzooplankton responses to an in situ iron fertilization experiment (SEEDS-II) in the northwest subarctic Pacific. *Deep-Sea Research II* 56 (26), 2767–2778.
- Tsumune, D., Nishioka, J., Shimamoto, A., Watanabe, Y.Y., Aramaki, T., Nojiri, Y., Takeda, S., Tsuda, A., 2009. Physical behavior of the iron fertilized patch in the SEEDS II. *Deep-Sea Research II* 56 (26), 2948–2957.

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