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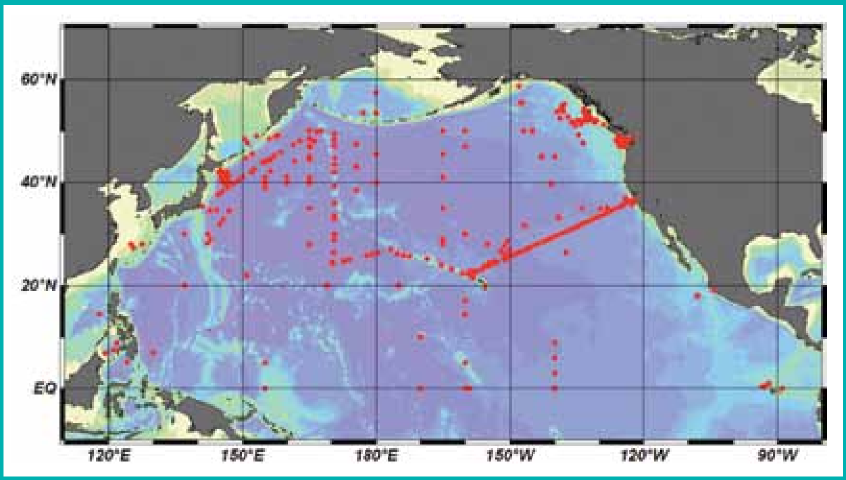

Report of Working Group 22 on Iron Supply and its Impact on Biogeochemistry and Ecosystems in the North Pacific Ocean

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Report of Working Group 22 on Iron Supply and its Impact on Biogeochemistry and Ecosystems in the North Pacific Ocean

Edited by
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Executive Summary

The Working Group on *Iron Supply and its Impact on Biogeochemistry and Ecosystems in the North Pacific Ocean* (WG 22) was established October 2007 under the direction of the Biological Oceanography Committee (BIO) and consisted of 20 members from all PICES member countries, including Co-Chairmen, Drs. Shigenobu Takeda (Japan) and Fei Chai (USA). The purpose of the Working Group was to examine the role of iron biogeochemistry and its impact on biological productivity and marine ecosystems.

WG 22 has completed the following four goals in its terms of reference:

1. Compile and synthesize available iron biogeochemistry data in the North Pacific;
2. Review the past and ongoing laboratory, field and modeling studies on iron biogeochemistry and its impact on biological productivity and marine ecosystems in the North Pacific Ocean;
3 Determine the natural supplies of iron to the North Pacific, which include atmospheric dust transport and movement of iron-enriched waters, and examine linkages between iron supply and ecosystem responses;
4. Identify gaps and issues related to experimental and modeling activities, encourage and plan national and international scientific programs on iron biogeochemistry and its impact on marine ecosystems in the North Pacific.

A fifth term of reference "Elucidate the role of iron as a potential regulator of harmful algal bloom (HAB) in coastal ecosystems of the North Pacific" was not addressed as the Group determined that there was some overlap on this topic between WG 22 and the Section on *Ecology of Harmful Algal Blooms in the North Pacific* (S-HAB) which could either be covered by the latter or incorporated into the activity plans of FUTURE (**F**orecasting and **U**nderstanding **T**rends, **U**ncertainty and **R**esponses of North Pacific Marine **E**cosystems), the second integrative science program of PICES.

Due to a lack of coordinated research projects among the PICES member countries, enthusiasm at times was less than optimal among members during the course of the Working Group's lifespan, but WG 22 did make notable progress in advancing our understanding on natural iron supplies and their impact on biogeochemical processes in the North Pacific Ocean through discussions at its annual business meetings, a BIO/SOLAS-sponsored workshop at PICES-2009 in Jeju, Korea, and BIO/SOLAS-sponsored topic session at PICES-2010 in Portland, USA.

The 2009 Workshop on "*Natural supplies of iron to the North Pacific and linkages between iron supply and ecosystem responses*" (see Appendix 4 for the 2009 annual activity report and accompanying workshop summary, with extended abstracts), hosted more than 30 participants. The presentations ranged from talks on iron measurements in the North Pacific and the iron modeling effort in the Fe-NEMURO model to field studies that related to iron sources, distribution, and iron impacts on phytoplankton dynamics in both the eastern and western subarctic Pacific. Modeling presentations summarized the latest developments in iron and biogeochemical modeling at regional and global scales.

The 2010 Topic Session on "*Understanding the role of iron in regulating biogeochemical cycles and ecosystem structures in the North Pacific Ocean*" (see Appendix 4 for the 2010 annual activity report and accompanying session summary), attended by about 50 people, generated interesting discussions on presentations covering a wide range of topics including iron chemistry, sources, transport and distribution, iron impacts on plankton dynamics and dimethylsulfide (DMS) production, the role of zooplankton in smoothing the geographical heterogeneity of primary productivity generated by iron availability and the potential of ocean fertilization to sequester carbon.

Some of the presentations made at the workshop and topic session have resulted in a series of publications, and these papers are listed in Appendix 3. These publications have greatly improved our understanding of iron supply and biogeochemical responses in the North Pacific, which was the focus of the WG 22. In addition, as one of the Working Group's terms of reference, Drs. Shigenobu Takeda and Mark Wells (member from USA) worked together to compile available iron measurements in the North Pacific (see http://www.pices.int/members/working_groups/Disbanded_working_groups/products/WG22_dissolved_iron_dataset.pdf).

At the last meeting of WG 22 in 2010, a new working group on "*Sensitivity of the North Pacific to Atmospheric Iron Deposition in a Low pH Ocean*" was proposed, with the main objective to determine how the predicted decrease in ocean pH will impact the response of the high nutrient low chlorophyll (HNLC) ecosystems to atmospheric iron deposition in the North Pacific. Although this proposal was not approved at the 2010 inter-sessional meeting of FUTURE in Seoul, Korea, it was recommended that "ecosystem responses to multiple stressors" be a topic for a new working group and that these stressors should include acidification, dust input, pH, and iron cycling.

In the meantime, there are some potential linkages between WG 22 activities and FUTURE. For example, data sets for iron and related parameters in the North Pacific can contribute to the improvement of marine ecosystem models that will be used for understanding biogeochemistry and climate forcing. A number of the papers published by the WG 22 scientists can provide useful suggestions for some of the activities of FUTURE's Advisory Panel on *Climate, Oceanographic Variability and Ecosystems* (AP-COVE) concerning the role of iron in regulating ecosystem responses to natural and anthropogenic forcing.

In summary, WG 22 has accomplished most of its originally proposed objectives. Through Annual Meetings, we kept the iron community in all PICES member countries together on a regular basis. Our Working Group members actively exchanged ideas and discussed their ongoing research results, which led to several important publications. We also consolidated some of available iron data for the North Pacific, and more data will be added to this data set as time goes on. We are confident that our short 3-year effort will provide a sound foundation for future iron-related research in the North Pacific Ocean.

Shigenobu Takeda and Fei Chai
Co-Chairmen

Working Group on *Iron Supply and its Impact on*
Biogeochemistry and Ecosystems in the North Pacific Ocean

1 Introduction

In the subarctic North Pacific Ocean, iron plays a central role in regulating phytoplankton productivity and pelagic ecosystem structure. There are several processes that supply iron from land, shelf sediment and deep waters to the upper ocean, including atmospheric deposition of mineral aerosols and combustion substances, lateral transport of coastal iron-enriched waters by eddies and boundary currents, and deep vertical mixing during winter or strong tidal currents at narrow straits.

There were three iron enrichment experiments conducted in the subarctic North Pacific Ocean to examine the role of iron on biological productivity and carbon flux. SEEDS-I and SEEDS-II (**S**ubarctic Pacific Iron **E**xperiment for **E**cosystem **D**ynamics **S**tudy) were carried out in the western subarctic Pacific in the summers of 2001 and 2004, respectively. SERIES (**S**ubarctic **E**cosystem **R**esponse to **I**ron **E**nrichment **S**tudy) was performed in the eastern subarctic Pacific in the summer of 2002. The PICES Advisory Panel on *Iron Fertilization Experiment in the Subarctic Pacific Ocean* (AP-IFEP; 1998–2007) coordinated international collaboration among the scientists involved in those experiments. Having completed its terms of reference, and before being disbanded, AP-IFEP proposed the establishment of a new Working Group on *Iron Supply and its Impact on Biogeochemistry and Ecosystems in the North Pacific Ocean* (WG 22). This Group was established in 2007 under the direction of the Biological Oceanography Committee (BIO) and was co-chaired by Drs. Shigenobu Takeda (Japan) and Fei Chai (USA). The purpose of WG 22 was to examine the role of iron biogeochemistry and its impact on biological productivity and marine ecosystems. This has been dealt with through the compilation of an extensive dissolved iron data set, including original references, for the subarctic North Pacific (Section 2), followed by an overview of iron biogeochemistry and its impact on biological productivity and marine ecosystems (Section 3), natural supplies of iron to the region (Section 4), modeling activities (Section 5), and recommendations for the future of iron biogeochemistry studies in PICES (Section 6). WG 22 terms of reference, membership, recent publications on iron supplies and biogeochemical responses, and annual reports, including workshop and topic session summaries, can found in Appendices 1–4.

2 Dissolved Iron Data Set of the North Pacific

Dissolved iron data of the North Pacific collected by WG 22 are compiled in an Excel file (available at http://www.pices.int/members/working_groups/Disbanded_working_groups/products/WG22_dissolved_iron_dataset.pdf) from 46 original papers listed below. A map of the stations and vertical profiles of the compiled data are shown in Figures 1 and 2, respectively. The data set includes dates, cruise #, position (station, depth), dissolved iron concentrations (filter sizes ranging from 0.2–0.45 µm) and references. The database is an expansion of that compiled by Moore and Braucher (2008).

All users of this data set are requested to include the original papers into the reference section of their articles.

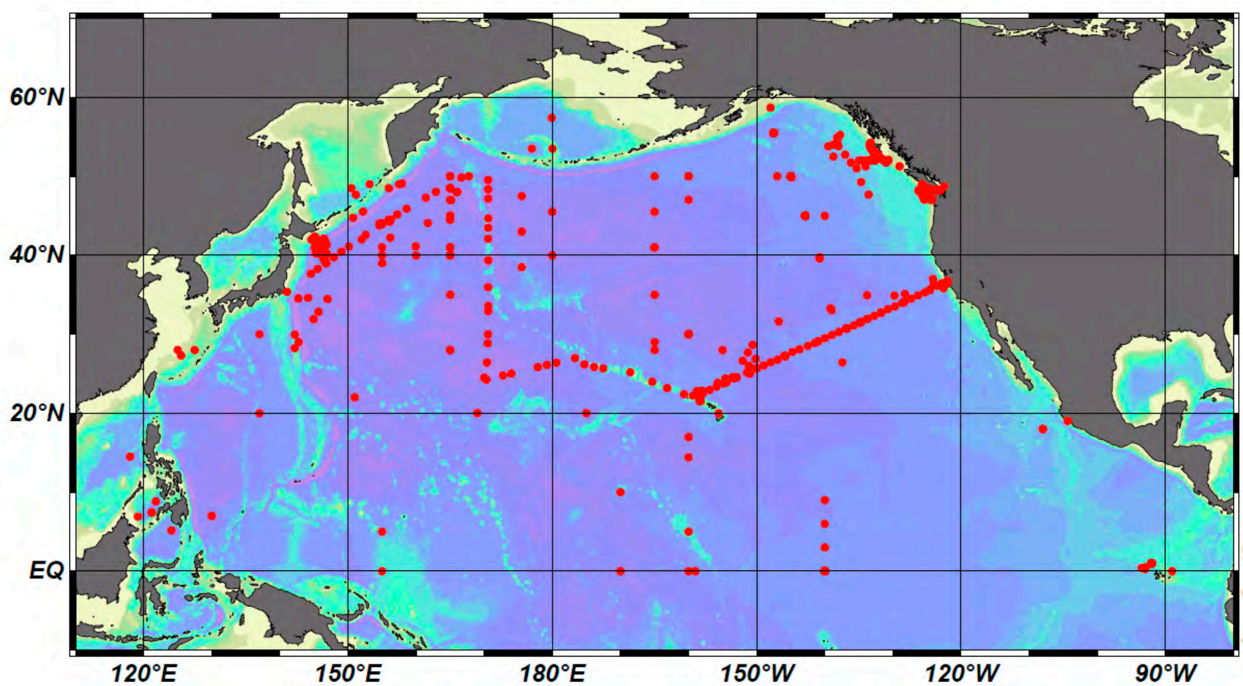

Fig. 1 Location of the sampling stations compiled in PICES WG 22's dissolved iron data set of the North Pacific Ocean.

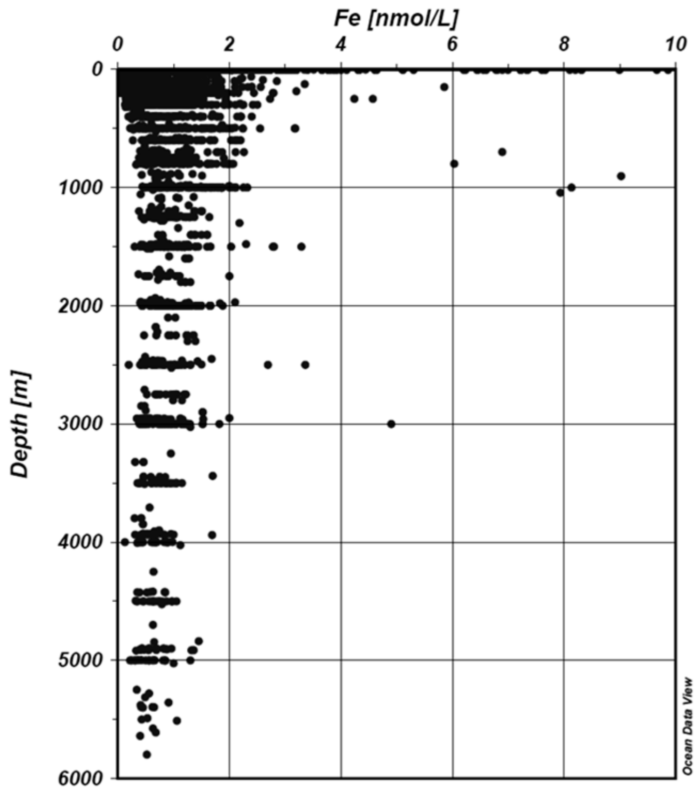

Fig. 2 Vertical profiles of the dissolved iron concentrations in the North Pacific Ocean.

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Original Iron Database

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3 Iron Biogeochemistry and its Impact on Biological Productivity and Marine Ecosystems in the North Pacific Ocean

Three open-ocean iron-enrichment experiments conducted in the Western Subarctic Gyre (SEEDS-I, 2001; SEEDS-II, 2004) and the Alaska Gyre (SERIES, 2002) have shown that iron availability exerts potential controls on phytoplankton growth, nutrient utilization, algal community composition, and the ecosystem structure in the subarctic North Pacific. In the natural ecosystem, atmospheric dust has been thought to be the most important source of iron, supporting annual biological production in the subarctic Pacific, especially in the western region (*e.g.*, Duce and Tindale, 1991). Although the iron supply from Asian dust events seems to have enough potential to stimulate phytoplankton productivity in the western subarctic North Pacific waters (Iwamoto *et al*., 2011), clear evidence from field observations is very limited (Young *et al*., 1991), suggesting a spatial and temporal mismatch of the dust inputs and biological activities. On the other hand, iron supply by airborne volcanic ash into the Pacific Ocean is comparable to the mineral dust input (Olgun *et al*., 2011) and basin-scale dispersions of volcanic ash have been shown to stimulate the primary production in nearly the whole area of the subarctic waters in summer (Hamme *et al*., 2010). Satisfying the algae demands for both light and iron is a key for phytoplankton blooming in high nutrient low chlorophyll (HNLC) waters, and it is interesting to compare the range in fluctuations of iron requirements under saturating and limiting light conditions between pennate and centric diatoms to better understand the influence of iron and light co-limitation in the competition between them for growth within distinct phytoplankton communities in the Eastern and Western Subarctic Gyres. The impact of increasing atmospheric deposition of anthropogenic soluble iron is another important topic for future study in the subarctic North Pacific (Krishnamurthy *et al*., 2009).

Studies by Nishioka *et al.* (2007, 2011) indicate that iron re-suspended from the sediments of the continental shelf is another important source of iron for the Western Subarctic Gyre. There is a relatively consistent and/or seasonal supply of iron through lateral transport from a marginal sea and continental margin as well as through vertical mixing during winter in the western (Oyashio) region. On the other hand, a restrictive supply of iron by mesoscale eddies, tidal currents, Ekman transport, and southeastward advection *via* the Alaska Gyre may produce relatively severe iron limitations in the eastern North Pacific region (Johnson *et al*., 2005) although iron from the continental margin might stimulate a wintertime phytoplankton bloom (Lam *et al*., 2006). It is possible that the sedimentary iron supply from the Sea of Okhotsk can be used to explain the difference in dissolved Fe distribution between the western and eastern subarctic Pacific (Nishioka *et al.*, 2003). Particulate Fe concentrations are also high in the water column of the western Pacific. The characteristics and behavior of particulate Fe can vary significantly from small colloidal inorganic mineral particles to large organic aggregates, which may include both living and dead components (Hurst and Bruland, 2007). Therefore, bioavailability of particulate Fe cannot be generalized, and elucidation of the key processes that regulate the transformation during lateral transport is a big challenge for both biogeochemists and modellers (Lam *et al*., 2006; Moore and Braucher, 2008; Fiechter *et al*., 2009; Fiechter and Moore, 2009).

Observed seasonality in dissolved Fe concentrations in the surface waters of the Oyashio region (Nishioka *et al*., 2011) indicates that, in addition to the traditional view of dust input, the iron transported by intermediate waters should be considered as an important source of iron for phytoplankton blooms in the Oyashio region and the Oyashio–Kuroshio transition zone. Sedimentary iron flux would be one of the major processes causing the difference in iron distribution and biological production between the

Western Subarctic Gyre and the Alaska Gyre. Phytoplankton blooms over the shallow continental shelf of the eastern Bering Sea may also be supported by sedimentary iron supply (Tyrrell *et al*., 2005).

To understand biogeochemical iron cycles in the subarctic North Pacific, it is essential to consider long-distance sedimentary-iron transportation. Recent field and modeling studies suggest that organic ligands, such as humic substances, play an important role in determining the basin-scale variation of dissolved iron distribution (Misumi *et al*., 2013; Uchida *et al*., 2013) but the transformation between dissolved and particulate phases and their interaction with organic ligands is still uncertain. The presence of relatively high concentrations of excess free organic ligands in the surface water may indicate the formation of iron-complexing organic ligands by phytoplankton release, grazing processes and viral cell lysis. Such processes could be more active in the western North Pacific where biological processes and cycling are working substantially more than in the eastern North Pacific (Selph *et al*., 2005). On the other hand, severe iron-limited conditions in the eastern region may stimulate the bacterial production of siderophores. Consequently, having a high-affinity iron transport system to take up iron from the siderophore-iron complex, which is known to operate in some oceanic-centric diatoms, could be one of the strategies for survival. However, the community half-saturation constant for growth with respect to iron was found to be similar between the Western and Eastern Subarctic Gyres (Takeda, 2011). In future work, we need to test the co-limitation of iron and other essential micronutrients such as zinc (Jakuba *et al*., 2012) and vitamin B_{12} (Koch *et al*., 2011).

In spite of high iron levels in coastal Oyashio water (Nakayama *et al*., 2010), it is hypothesized that iron availability controls the growth of phytoplankton in some parts of the Oyashio region (Hattori-Saito *et al*., 2010; Takeda, 2011). However, there is no clear relationship between photosynthetic physiology of the phytoplankton assemblage dominated by micro-sized diatoms and dissolved iron concentrations during a spring bloom in the Oyashio region (Yoshie *et al*., 2010; see Hattori-Saito *et al*., extended abstract, page 42), suggesting that the changes in photosynthetic parameters are caused by the shift in dominant diatom species having different iron requirements and/or intracellular iron pools (Sugie *et al*., 2011).

In the pelagic food web, top-down control may also have an influence on the response of biological productivity to iron supply. The increases in large, long-setae, or heavily silicified diatoms during the high grazing pressure period in the SEEDS-II experiment have been attributed to anti-predation from copepods (Tsuda *et al*., 2009) and it strongly suggests that both moderate iron supply and active mesozooplankton grazing may lead the phytoplankton assemblage to be dominated by large centric diatoms in the Western Subarctic Gyre. In the Alaska Gyre, low Fe:C ratio and high iron usage efficiency would be advantageous for coccolithophorids and pennate diatoms to survive in consistently low iron conditions (Wells, 2003) with additional prominence for pennates that have an extensive iron-storage ability (Marchetti *et al*., 2009) for sporadic iron supply from the atmosphere or from continental shelf sediments.

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4 Natural Supplies of Iron to the North Pacific

In the last three decades, marine geochemists have made significant progress in the techniques for studying biogeochemistry of trace elements. The advances in the sampling protocols and analytical techniques provide unprecedented capability for measurement of a wide distribution of trace elements. Determining the distribution of iron in the ocean, including the processes involved in oceanic cycles, is important for understanding the biological production of the ocean and its impact on the biogeochemical cycle and climate (Boyd and Ellwood, 2010). To date, we have understood that various iron sources occur in the North Pacific, such as atmospheric dust (*e.g*., Duce and Tindale, 1991), re-suspension of sediments on the shelf (*e.g*., Elrod *et al*., 2004), lateral transport of coastal iron-enriched waters by eddies and boundary currents (*e.g*., Lam *et al*., 2006), iron supply from below the surface by deep vertical mixing during winter or by strong tidal currents at narrow straits (Nishioka *et al*., 2011), and iron supply from volcanism (*e.g*., Duggen *et al*., 2007).

Atmospheric dust has been considered to be the most important source of iron in the North Pacific. Previous studies indicate that there is a longitudinal dust gradient across this region. The flux of dust containing iron over the western subarctic Pacific is an order of magnitude higher than that in the eastern side (*e.g*., Duce and Tindale, 1991; Mahowald *et al*., 2005; Measures *et al*., 2005). This is due to the closer proximity to the second largest dust source in the world, the Gobi desert, and this is believed to be the leading cause for the longitudinal differences in biological production between the western and the eastern subarctic Pacific (Harrison *et al*., 2004). Although the role of iron dust supply to biological production has not been quantitatively evaluated, a few studies have revealed a connection between the atmospheric iron dust supply and enhanced biological production. Bishop *et al.* (2002) reported that high-frequency observations of upper ocean particulate organic carbon variability showed a near doubling of biomass in the mixed layer over a 2-week period after the passage of a cloud of Gobi desert dust. Hamme *et al.* (2010) found that volcanic ash deposition in August 2008 initiated one of the largest phytoplankton blooms observed in the subarctic North Pacific. Unusually widespread transport from a volcanic eruption in the Aleutian Islands, Alaska, deposited ash over much of the subarctic Northeast Pacific, followed by large increases in chlorophyll, observed by satellite imagery. Surface ocean pCO_2, pH, and fluorescence revealed that the bloom started a few days after the ashfall. The importance of glacial flour dust storms in the Gulf of Alaska (GoA) has also been suggested by Crusius *et al.* (2011).

On the other hand, many previous studies have postulated that re-suspended particles from continental shelf sediments are a primary source of iron for phytoplankton in the coastal upwelling zone (Johnson *et al*., 1999; Bruland *et al*., 2001; Elrod *et al*., 2004; Bruland *et al*., 2005; Kudela *et al*., 2006; Cullen *et al*., 2009). Wu *et al.* (2009) also indicated that variations in surface water iron concentrations in the northern GoA from spring through summer appear to result from the changes in freshwater discharge and physical processes on the shelf. In addition, the naturally occurring high-chlorophyll regions that develop at the boundaries of these iron-limited HNLC waters and nitrate-poor, iron-rich coastal waters are reported in several studies. For instance, Aguilar-Islas *et al.* (2007) and Hurst *et al.* (2010) have examined the “green belt” that occurs at the shelf break in the southeastern Bering Sea, and they propose an “iron curtain” hypothesis. Details of the iron supply mechanisms at the shelf break of the “green belt” by turbulent mixing processes has also been studied by Tanaka *et al.* (2012).

Attention also has been drawn to long-distance horizontal transport of iron-rich coastal waters offshore (Harrison *et al.*, 2004). The re-suspended particles from continental shelf sediments are included into bottom water and the iron-containing water can be moved over long distances by water transport systems. Eddy transport from the continental margin is an important process for supplying iron to the oceanic part of the GoA (Johnson *et al*., 2005; Rovegno *et al*., 2009; Lippiatt *et al*., 2010, 2011; Xiu *et al*., 2011). Lippiatt *et al*. (2011) carried out a major field study to test the hypothesis that regions of high biomass observed in satellite imagery in the northern GoA in mid-summer are due to the high river and glacial melt runoff during this time of year into the Alaska Coastal Current (ACC), enriching the ACC with both dissolved and leachable particulate Fe, and the resultant mixing of this high iron coastal water with the HNLC waters of the adjacent GoA *via* mesoscale anti-cyclonic eddies. They examined the roles of Kenai Eddies, 100 to 200 km in diameter, in transporting dissolved and leachable particulate Fe from the shelf regions to offshore into the open GoA. They demonstrated the importance of eddies to the GoA in both the summer season and subsequent seasons.

Other long-distance iron transport processes have reported. The re-suspended sedimentary iron from the continental margin and the continental shelf of marginal seas is transported by boundary currents, and becomes an important source of iron into both the western and eastern sides of the subarctic Pacific. Lam *et al*. (2006) showed clearly that Ocean Station Papa (OSP) in the GoA received a lateral supply of particulate Fe from the continental margin off the Aleutian Islands in the winter, coincident with an observed biological bloom. In the western subarctic Pacific, Nishioka *et al.* (2007) reported that sedimentary iron was discharged from a sub-polar marginal sea, the Sea of Okhotsk, into the western North Pacific by the intermediate layer water transport system, which is driven by sea ice formation processes. There are additional reports that iron particles of volcanic origin from the Kuril/Kamchatka margins are sources to the western subarctic Pacific (Lam and Bishop, 2008). Although the solubility of iron from volcanic particles is not perfectly understood yet, it is possible that a supplement of additional iron input from the Kuril/Kamchatka volcanic margin occurs and is transported by the water system to the Western Subarctic Gyre (Lam and Bishop, 2008). These iron-rich water transports play critical roles in supporting biological production, such as massive phytoplankton spring blooms in the Oyashio region in the western subarctic Pacific (Nishioka *et al*., 2011). Another long-distance iron transport system was found in the New Guinea Coastal Undercurrent (NGCU) and the Equatorial Under Current (EUC) in the western equatorial Pacific. The NGCU waters are enriched with iron and the iron is mobilized in a highly active western boundary current region and transported eastward in the lower EUC (Mackey *et al.*, 2002; Slemons *et al*., 2010), supporting biological production in the eastern equatorial Pacific (Wells, 1999).

These studies provide insight into the mechanisms of iron supply to the North Pacific and key biogeochemical pathways of reactive forms of iron that should be introduced in ecosystem models. These multiple iron sources and related physical processes should be considered for understanding biological production in the North Pacific.

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5 Modeling Activities

Iron deficiency limits primary production in high-nutrient, low-chlorophyll (HNLC) regions: the subarctic North Pacific (Martin and Fitzwater, 1988; Tsuda *et al*., 2003; Boyd *et al*., 2004), and indirectly controls the production in the nitrogen-limited subtropics by limiting N_2 fixation (Michaels *et al*., 1996; Falkowski, 1997; Kustka *et al*., 2003; Morel and Price, 2003; Mills *et al*., 2004; Moore and Doney, 2007). Thus, iron is a key element for understanding marine biogeochemistry and the marine ecosystem. Therefore, it is important that the mechanisms of iron supply to the North Pacific and the key biogeochemical pathways of reactive forms of iron should be introduced into biogeochemical and/or ecosystem models.

A growing amount of field data on dissolved iron concentrations is improving our understanding of oceanic iron distribution, sources and important physical processes of iron supply, and is guiding the development of iron cycle models. Field data for the North Pacific was compiled by Johnson *et al*. (1997). (Further accumulation of field data has revealed inter-ocean gradients of dissolved iron concentrations (de Baar and de Jong, 2001; Gregg *et al*., 2003; Parekh *et al*., 2005; Moore and Braucher 2008)). Johnson's data exhibited a nutrient-type vertical profile with concentrations in deep water roughly converging to 0.6 nM without significant inter-ocean differences. Based on these observations, they proposed an iron cycle model where complexation by strong iron-binding ligands reduces iron scavenging rates at concentrations less than a presumed ligand concentration of 0.6 nM. From this concept, Archer and Johnson (2000) introduced explicit kinetics for iron and the binding ligands and incorporated it into a three-dimensional General Circulation Model (GCM); the results confirmed the importance of iron complexation. Parekh *et al.* (2004) conducted box-model experiments to examine a large parameter for investigating iron scavenging. Parekh *et al.* (2005) incorporated the iron model and optimized parameters into a GCM and successfully simulated differences in basin-scale iron concentrations in the World Ocean.

Spatial distributions of external iron sources should be considered to represent a more realistic iron cycle in the ocean. Most early studies assumed that aeolian dust is the dominant iron source to the open ocean (Duce and Tindale, 1991), and early-stage models only included this source of iron for external sources (*e.g*., Fung *et al*., 2000) but continental margin sediments have recently been regarded as an important source of iron (Elrod *et al*., 2004). Both the aeolian and sedimentary sources are now incorporated into a number of numerical models (Moore *et al*., 2004; Moore and Braucher, 2008; Parekh *et al*., 2008). Sensitivity experiments either prescribing aeolian or sedimentary sources have suggested that sedimentary iron contributes to some open ocean regions, particularly in the North Pacific (Moore and Braucher, 2008).

Numerous models have been established to represent the atmospheric iron supply (*e.g*., Luo *et al*., 2008; Mahowald *et al*., 2009), responses of iron enrichment experiment experiments (*e.g*., Fujii *et al.*, 2005; Yoshie *et al.*, 2005; Takeda *et al*., 2009; Denman *et al*., 2009), iron limitation in specific locations due to physical and chemical processes (Dutkiewicz *et al*., 2009; Fiechter *et al*., 2009; Shigemitsu *et al*., 2012), iron transport by eddies and boundary currents (*e.g*., Lam *et al*., 2006; Xiu *et al*., 2011), iron speciation (colloidal, binding ligands (*e.g*., Parekh *et al*., 2008; Misumi *et al*., 2011), and iron supply to diazotrophs (*e.g*., Moore and Doney, 2007) in the North Pacific.

Modelers have made significant progress in constructing ocean ecosystem and biogeochemical models for studying iron-related issues in the North Pacific. However, there are still gaps and issues related to experimental and modeling activities on iron cycle studies in the subarctic North Pacific. With respect to atmospheric dust input to the surface ocean, one of the largest uncertainties entails the percentage of iron dissolution from different types of dust. Similarly, the extent of dissolution or biological availability of suspended particulate Fe, especially the continental source from rivers and re-suspended sediments, is a large uncertainty.

In coastal areas with high concentrations of suspended terrigenous particles with iron coatings, the concentration of strong Fe(III)-binding organic ligands appears to control the dissolved Fe concentrations. The large excess of leachable particulate Fe acts as a capacitor or buffer to supply dissolved Fe to essentially titrate the strong Fe(III)-binding organic ligands. Leachable particulate Fe is a far more important source of iron than has been realized. An important question is the residence time of particulate Fe in the relatively long-lived eddies. Location of the continental shelf in relation with water formation and current direction, especially in the mesopelagic layer, is an important factor for controlling sedimentary iron transportation in the subarctic Pacific. The model should include these processes with high resolution water circulation.

The main form of iron, which is supplied from sedimentary sources, is in particulate form. We need to know the spatial change of the particulate Fe bio-availability which contributes to phytoplankton growth. We need more experiments, and more observations, for evaluating its bio-availability. Models should represent particulate Fe with changing bioavailability. In addition, modeling studies can be used to suggest the dominant processes to explain the upward iron transport from the intermediate water to the surface layer, *e.g.*, tidal mixing, winter mixing, Ekman transport, *etc*. Chemical iron speciation and its distribution and cycle in the ocean are not well established owing to the analytical difficulty in measuring iron and its complex chemical nature in seawater. The dynamics and sources of ligands in the ocean are still unclear.

Large-scale iron ocean fertilization experiments have shown that iron dust can increase, albeit modestly, carbon sequestration, and can significantly affect the production and flux of dimethylsulfide (DMS) and other trace gases to the atmosphere (see reviews in *Marine Ecology Progress Series*, 2008, vol. 364, pp. 213–309). In several of these experiments, the dynamics of carbon and DMS were tightly coupled to the early blooms of calicifying prymnesiophytes, which are highly sensitive to variations in pH. Thus, the predicted decrease in oceanic pH could affect their response to iron availability. This could significantly alter the impact of atmospheric iron deposition on the North Pacific ecosystems. This important issue should be addressed through onboard and *in situ* mesocosm experiments with a series of treatments, such as additions of dust, Fe, CO_2, and Fe+CO_2. The results from these experiments may encourage development of new ecosystem models which can assess the impact of iron deposition on primary production, and global climate in a high CO_2 world.

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6 Recommendations for the Future of Iron Biogeochemistry Studies within PICES

During its final meeting at PICES-2010 in Portland, USA, WG 22 discussed basic questions regarding the future of iron studies within PICES and agreed that the next phase of iron research in the North Pacific should cover:

- ecosystem responses to changes in iron supply rates, amounts, and pathways,
- dissolution or biological availability and residence time of suspended particulate Fe (from rivers, resuspended sediments, industrial combustion, and dust),
- mechanisms controlling chemical speciation of iron in seawater and interaction of iron binding organic ligands with particulate Fe,
- dynamics of iron binding organic ligands,
- interactions of iron with other stressors such as pH, Cu, *etc*.

For improving ecosystem models that include an iron cycle, more information is needed on:

- iron removal and recycling,
- iron sources,
- physiology of co-limitation by iron and other parameters,
- grazing on phytoplankton communities.

The Working Group agreed that a better understanding of the iron supply is required before they can get ecosystems right, but they also need to get ecosystems right before they can get the iron concentration right.

WG 22 recommended that PICES support:

- integration of regional studies on iron biogeochemical cycles and its ecosystem impacts,
- development of a North Pacific data base for iron and related parameters,
- symposium/annual meeting sessions on the role of iron in regulating ecosystem responses to natural and anthropogenic forcing in the North Pacific,
- model inter-comparisons activities.

Term of reference 5 "Elucidate the role of iron as a potential regulator of harmful algal bloom (HAB) in coastal ecosystems of the North Pacific" was not fully taken up for discussion in WG 22. Therefore, it is suggested that this topic could be incorporated into the activity plans of the Section on *Ecology of Harmful Algal Blooms in the North Pacific* and/or FUTURE.

Although WG 22's proposal for a new working group on "*Sensitivity of the North Pacific to Atmospheric Iron Deposition in a Low pH Ocean*" (see proposal in the PICES-2010 report of WG 22, Appendix 4) was not accepted, some of its emerging issues were incorporated into the mandate of Working Group on *Development of Ecosystem Indicators to Characterize Ecosystem Response to Multiple Stressors*, selected by FUTURE's Advisory Panel on *Climate, Oceanographic Variability and Ecosystems*, and established in June 2011.

Appendix 1

WG 22 Terms of Reference

1. Compile and synthesize available iron biogeochemistry data in the North Pacific;
2. Review the past and ongoing laboratory, field and modeling studies on iron biogeochemistry and its impact on biological productivity and marine ecosystems in the North Pacific Ocean;
3. Determine the natural supplies of iron to the North Pacific, which include atmospheric dust transport and movement of iron-enriched waters, and examine linkages between iron supply and ecosystem responses;
4. Identify gaps and issues related to experimental and modeling activities, encourage and plan national and international scientific programs on iron biogeochemistry and its impact on marine ecosystems in the North Pacific;
5. Elucidate the role of iron as a potential regulator of harmful algal bloom (HAB) in coastal ecosystems of the North Pacific.

Appendix 2

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Appendix 3

Some Recent Publications on Iron Supplies and Biogeochemical Responses

Brzezinski, M.A., Baines, S.B., Balch, W.M., Beucher, C.P., Chai, F., Dugdale, R.C., Krause, J.W., Landry, M.R., Marchi, A., Measures, C., Nelson, D.M., Parker, A., Poulton, A., Selph, K., Strutton, P., Taylor, A. and Twining, B. 2010. Co-limitation of diatoms by iron and silicic acid in the equatorial Pacific. *Deep Sea Res. II* **58**: 493–511, doi:10.1016/j.dsr2.2010.08.005.

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Schroth, A.W., Crusius, J., Chever, F., Bostick, B.C. and Rouxel, O.J. 2011. Glacial influence on the geochemistry of riverine iron fluxes to the Gulf of Alaska and effects of deglaciation. *Geophys. Res. Lett.* **38**: L16605, doi:10.1029/2011GL048367.

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Appendix 4

WG 22 Annual Reports and Topic Session/Workshop Summaries

PICES Seventeenth Annual Meeting, PICES-2008
October 24–November 2, 2008
Dalian, People's Republic of China

REPORT OF WG 22 ON *IRON SUPPLY AND ITS IMPACT ON BIOGEOCHEMISTRY AND ECOSYSTEMS IN THE NORTH PACIFIC OCEAN*

The Working Group on *Iron Supply and its Impact on Biogeochemistry and Ecosystems in the North Pacific Ocean* (WG 22) held its first meeting on October 25, 2008 from 11:00 to 18:00 under the co-chairmanship of Drs. Fei Chai and Shigenobu Takeda. Members who attended the meeting are listed in *WG 22 Endnote 1* and the meeting agenda can be found in *WG 22 Endnote 2*. The planned schedule and timeline of the Working Group is summarized below:

<u>October 2007</u>
PICES XVI (Victoria, Canada)
- Disbandment of the Advisory Panel on *Iron Fertilization Experiment in the Subarctic Pacific Ocean* (IFEP-AP)
- Establishment of a new Working Group (WG 22), under the direction of Biological Oceanography Committee (BIO)

<u>October 2008</u>
PICES XVII (Dalian, China)
- first WG 22 meeting

<u>October 2009</u>
PICES-2009 (Jeju, Korea)
- second WG 22 meeting (Workshop)

<u>October 2010</u>
PICES-2010 (Portland, U.S.A)
- third (final) WG 22 meeting (PICES Scientific Report)

AGENDA ITEM 2
Review of WG 22 Terms of Reference

Terms of reference for the Working Group were examined and adopted without revision (*WG 22 Endnote 3*).

AGENDA ITEMS 3 AND 4
Overview on atmospheric deposition of iron in the North Pacific and on vertical and horizontal supplies of iron in the North Pacific

Dr. Chai presented an overview on the atmospheric deposition of iron in the North Pacific Ocean on behalf of Dr. Natalie Mahowald; Dr. Jun Nishioka talked about horizontal iron supplies in the western subarctic Pacific; Dr. Mark Wells discussed the effects of mesoscale eddies in transporting iron in the eastern subarctic Pacific.

AGENDA ITEM 5
Review of national and international, past and ongoing activities on iron biogeochemistry

National reports were given by Canada (Maurice Levasseur), China (Zhongyong Gao) and the U.S.A. (Mark L. Wells). International reports and activities discussed at the meeting consisted of:

- SCOR working group on synthesizing previous ocean iron fertilization data (Shigenobu Takeda),
- Chinese SOLAS project and Asian Dust and Ocean EcoSystem (ADOES) (S. Tan),
- IOC/WESTPAC (Mitsuo Uematsu),
- Natural Fe Lagrangian Experiments (FeLEX) in the Southern Ocean (Meng Zhou),
- London Convention on Ocean Iron Fertilization (Patricio Bernal and Fei Chai).

Dr. Chai attended the London Convention Scientific Meeting on Iron Fertilization (May 19–23, 2008) where he provided a brief description of PICES and its function to the meeting Scientific Groups. He noted that:

- PICES scientists had been involved in 6 out of 12 iron fertilization experiments during the past 15 years and that PICES has provided a platform to facilitate research activities on ocean iron fertilization (OIF) experiments in the North Pacific. The Advisory Panel on *Iron Fertilization Experiment in the Subarctic Pacific Ocean* was formed under the PICES, and had been responsible for coordinating three OIF experiments in the subarctic Pacific. The Advisory Panel not only helped to coordinate the field experiments, but also facilitated data synthesized and publications.
    - The newly established Working Group (WG 22), *Iron Supply and its Impact on Biogeochemistry and Ecosystems in the North Pacific Ocean*, co-chaired by Drs. Shigenobu Takeda (Japan) and Fei Chai (U.S.A.) will focus on two primary goals for the next three years: a) to promote better understanding of natural and anthropogenic iron supplies to the North Pacific and their impact on biogeochemistry and ecosystems; and b) to facilitate closer ties among various research communities (aerosol, physical oceanography, biology, chemistry and modeling) to better integrate new findings and to provide needed feedback to help coordinate research activities.
- In regard to future OIF experiments, PICES can act as an independent scientific organization, and is willing to provide scientific expertise on future OIF experiments in the North Pacific Ocean, including independent evaluation and assessments. The review process will be for the interests of advancing scientific knowledge and potential impact on marine ecosystems in the North Pacific.

AGENDA ITEM 6
Work plan for implementing the Terms of Reference

A work plan, consisting of the following points, was discussed for implementing the Terms of Reference:

- Develop a North Pacific Fe database (Takeda and Wells),
- Determine the natural supplies of iron to the North Pacific (atmospheric dust transport; movement of iron-enriched waters),
- Examine the linkages between iron supply and ecosystem responses,
- Plan national and international scientific programs,
- Set basic questions and make a hypothesis for future iron-related activities in the North Pacific,
- Plan international scientific programs for testing the hypothesis,
- Perform joint cruises,
- Conduct modeling studies (Chai and Yamanaka).

AGENDA ITEM 7
Proposal for a 1-day workshop at PICES-2009

WG 22 proposed a 1-day workshop on natural supplies of iron to the North Pacific to be held at PICES-2009 in Jeju, Korea (*WG 22 Endnote 4*). Recommended co-convenors for the workshop are: Shigenobu Takeda

(Japan), Fei Chai (U.S.A.), and William R. Crawford (Canada). Travel support is requested for two scientists to attend the workshop, one scientist on iron biogeochemistry (Ken Bruland, U.S.A.) and another on ecological modelling (Yamanaka, Japan).

WG 22 Endnote 1

WG 22 participation list

Members	Observers
Fei Chai (U.S.A., Co-Chairman)	not available
William P. Cochlan (U.S.A.)	
Zhongyong Gao (China)	
Paul J. Harrison (Canada)	
Kyung-Ryul Kim (Korea)	
Maurice Levasseur (Canada)	
Jun Nishioka (Japan)	
Hiroaki Saito (Japan)	
Suzanne Strom (U.S.A.)	
Shigenobu Takeda (Japan, Co-Chairman)	
Charles Trick (Canada)	
Mitsuo Uematsu (Japan)	
Mark L. Wells (U.S.A.)	
Yasuhiro Yamanaka (Japan)	

WG 22 Endnote 2

WG 22 meeting agenda

1. Welcome and introductions (Co-Chair), and adoption of agenda
2. Review of WG 22 terms of reference
3. Overview on atmospheric deposition of iron in the North Pacific
4. Overview on vertical and horizontal supplies of iron in the North Pacific
   - Jun Nishioka: Horizontal supplies of iron in the western subarctic Pacific
   - Mark Wells: Effects of mesoscale eddies in transporting iron in the eastern subarctic Pacific
5. Review of national and international, past and ongoing activities on iron biogeochemistry and its impact on marine ecosystems in the North Pacific Ocean
   - National: Canada [M. Levasseur]; China [Z. Gao]; Japan [S. Takeda]; U.S.A. [M.L. Wells];
   - International: SCOR working group on synthesizing previous OIF data [S. Takeda] Chinese SOLAS project and Asian Dust and Ocean EcoSystem (ADOES) [S. TAN] IOC/WESTPAC [M. Uematsu]
   - London Convention on Ocean Iron Fertilization [P. Bernal and F. Chai]
   - Natural Fe Lagrangian Experiments (FeLEX) in the Southern Ocean [M. Zhou]
6. Develop a detailed work plan for implementing the Terms of Reference
7. Proposal for a one-day workshop at PICES-2009

WG 22 Endnote 3

WG 22 Terms of Reference

1. Compile and synthesize available iron biogeochemistry data in the North Pacific;
2. Review the past and ongoing laboratory, field and modeling studies on iron biogeochemistry and its impact on biological productivity and marine ecosystems in the North Pacific Ocean;
3. Determine the natural supplies of iron to the North Pacific, which includes atmospheric dust transport and movement of iron-enriched waters, and examine linkages between iron supply and ecosystem responses;
4. Identify gaps and issues related to experimental and modeling activities, encourage and plan national and international scientific programs on iron biogeochemistry and its impact on marine ecosystems in the North Pacific;
5. Elucidate the role of iron as a potential regulator of harmful algal bloom (HAB) in coastal ecosystems of the North Pacific.

WG 22 Endnote 4

Proposal for a 1-day workshop at PICES-2009 on
"Natural supplies of iron to the North Pacific and linkages between iron supply and ecosystem responses"

In the subarctic North Pacific Ocean, iron plays a central role in regulating phytoplankton productivity and pelagic ecosystem structure. There are several processes that supply iron from land, shelf sediment and deep waters to the upper ocean. The goal of this workshop is to examine key processes of these iron supply processes that includes atmospheric deposition of mineral Aerosols and combustion substances, lateral transport of coastal iron-enriched waters by eddies and boundary currents, and deep vertical mixing during winter or by strong tidal current at narrow strait. Such knowledge will be used to identify key biogeochemical pathway that should be introduced into the ecosystem models and to plan international scientific programs for better understandings of marine ecosystem responses to changing iron supplies in the North Pacific.

PICES Eighteenth Annual Meeting, PICES-2009
October 23–November 1, 2009
Jeju, Republic of Korea

REPORT OF WORKING GROUP 22 ON IRON SUPPLY AND ITS IMPACT ON BIOGEOCHEMISTRY AND ECOSYSTEMS IN THE NORTH PACIFIC OCEAN

The Working Group on *Iron Supply and its Impact on Biogeochemistry and Ecosystems in the North Pacific Ocean* (WG 22) held its second meeting on October 25, 2009 from 14:00 to 18:00 under the co-chairmanship of Drs. Fei Chai and Shigenobu Takeda who welcomed the participants and called the meeting to order. Members who attended the meeting are listed in *WG 22 Endnote 1*.

Unfortunately, the Working Group lost one of its members, Prof. Xiuren Ning, from China, who died from an automobile accident in France. At the beginning of the meeting, members and observers held one minute of silence to pay tribute to Prof. Ning.

Drs. Chai and Takeda reviewed its Terms of Reference, and reported on the progress and activities of the Working Group during the past year. Dr. Takeda talked about the SCOR working group on synthesizing ocean iron fertilization data and future modeling activities (WG 131 on The Legacy of in situ Iron Enrichment: Data Compilation and Modeling). Dr. Chai presented the U.S. position statement on large-scale iron fertilization experiments. Both Co-Chairmen reported on the London Convention Scientific Working Group and IOC *ad hoc* committee activities on ocean fertilization. Dr. Maurice Levasseur (member from Canada) was unable to attend the meeting, but prepared a document calling for international research collaboration on iron-dust deposition in the HNLC regions considering a pH decrease in the ocean. The Working Group reviewed the 1-day workshop (W1) on "*Natural supplies of iron to the North Pacific and linkages between iron supply and ecosystem responses*" held October 25, 2009 and co-sponsored by BIO and SOLAS (see list of participants and workshop summary on page 34).

A proposal for a Topic Session on "*Understanding the role of iron in regulating biogeochemical cycles and ecosystem structures in the North Pacific Ocean*" was put forth for PICES-2010 in Portland, U.S.A. (*WG 22 Endnote 2*). The Topic Session will be co-sponsored by SOLAS. Convenors have been selected and invited speakers have been proposed, but not yet confirmed. Travel support for two invited speakers is requested from PICES.

WG 22 Endnote 1

WG 22 participation list

<u>Members</u>

Fei Chai (USA, Co-Chairman)
William Crawford (Canada)
Jun Nishioka (Japan)
Hiroaki Saito (Japan)
Vladimir Shulkin (Russia)
Shigenobu Takeda (Japan, Co-Chairman)
Mark Wells (USA)

<u>Observers</u>

Kenneth Bruland (USA)
Stephanie Dutkiewicz (USA)
Masahiko Fujii (Japan)
Ai Hattori-Saito (Japan)
Guimei Liu (China)
Tsuneo Ono (Japan)
Hiroshi Sumata (Japan)
Toru Suzuki (Japan)
Keisuke Uchimoto (Japan)
Atsushi Tsuda (Japan)

WG 22 Endnote 2

Proposal of a 1-day Topic Session on
"*Understanding the role of iron in regulating biogeochemical cycles and ecosystem structures in the North Pacific Ocean*" at PICES-2010

Iron plays a key role in regulating the biogeochemical cycles of carbon and nitrogen, and pelagic ecosystem structures in the North Pacific Ocean, yet our understanding of these effects remains limited. External sources of iron, such as Asian dust, rivers, sediments, and volcanoes supply large amounts of iron to the North Pacific, while the physical processes of upwelling, meso-scale eddies, boundary currents, and tidal mixing transport deep waters with high iron concentration to the upper ocean. Biological uptake, zooplankton grazing, remineralization, and iron chemistry change the forms of iron and its distribution in the North Pacific Ocean. This session invites papers that address physical, biological and chemical processes controlling iron distribution and transformation, linkages between iron and ecosystem responses, and impacts on carbon and nitrogen cycles. We particularly invite papers that combine recent progress from field observations and modeling studies that relate iron cycling to ecosystem structures and carbon fluxes in the North Pacific Ocean.

Co-convenors: Mark Wells (USA), Angelica Peña (Canada), and Toshi Saino (Japan)

Suggested invited speakers:
Keith Moore (USA)
Phoebe Lam (USA)
Hajime Obata (Japan)
One modeler outside PICES countries, who develops more detailed iron chemistry
Jay Cullen (Canada)
Maurice Levasseur (Canada)

PICES Eighteenth Annual Meeting Workshop Summary

W1 participation list

Canada
James Christian
William Crawford
David Mackas
Charles Trick

Japan
Masahiko Fujii
Ai Hattori-Saito
Sachihiko Itoh
Ryo Kimura
Chihiro Miyazaki
Jun Nishioka
Masami Nonaka
Yuji Okazaki
Tsuneo Ono
Hiroaki Saito
Hiroshi Sumata
Shigenobu Takeda
Atsushi Tsuda
Keisuke Uchimoto
Hiromichi Ueno
Yutaka Watanuki
Yasuhiro Yamanaka
Ichiro Yasuda

Russia
Vladimir Shulkin

USA
Kenneth Bruland
Fei Chai
Michael Dagg
Stephanie Dutkiewicz
Carol Ladd
Phillip Mundy
Chang Seung
Mark Wells

Organizations
Sonia Batten (SAHFOS)
Alexander Tkalin (NOWPAP)

BIO Workshop (W1)
Natural supplies of iron to the North Pacific and linkages between iron supply and ecosystem responses

Co-sponsored by SOLAS
Co-Convenors: Fei Chai (U.S.A.), William R. Crawford (Canada) and Shigenobu Takeda (Japan)

<u>Background</u>

In the subarctic North Pacific Ocean, iron plays a central role in regulating phytoplankton productivity and pelagic ecosystem structure. There are several processes that supply iron from land, shelf sediment and deep waters to pelagic ecosystem. The goal of this workshop was to examine the relative importance of these iron supply processes that includes atmospheric deposition of mineral aerosols and combustion substances, lateral transport of coastal iron-enriched waters by eddies and boundary currents, and deep vertical mixing during winter or by strong tidal current at narrow strait. Such knowledge will be used to identify key biogeochemical pathway that should be introduced into the ecosystem models and to plan international scientific programs for better understandings of marine ecosystem responses to changing iron supplies in the North Pacific.

Summary of Presentations

The workshop, sponsored by the BIO Committee and SOLAS, was the first workshop organized by the Working Group on *Iron Supply and its Impact on Biogeochemistry and Ecosystems in the North Pacific Ocean* (WG 22). The 1-day workshop was held on October 25, and consisted of two parts. The first part included a total of 9 oral presentations and one poster, and it lasted from 9:00 to 15:30 h. The second part was WG 22's first business meeting, which was conducted from 16:00 to 18:00 h. The workshop had more than 30 participants representing all PICES member countries. Six talks in the morning focused on the field studies that related to iron sources, distribution, and iron impacts on phytoplankton dynamics in both the eastern and western subarctic Pacific. Three modeling presentations summarized the latest development of iron and biogeochemical modeling at regional and global scales.

Discussion following these talks focused on the gaps and issues related to experimental and modeling activities on iron biogeochemistry and its impact on ecosystem structures and carbon cycle. Here are some highlights of our discussion: 1) atmospheric dust input and Fe solubility are associated with different types of dusts, including volcanic Fe input; 2) the role of eddies and coastal currents are important in transporting Fe, especially sedimentary sources of different forms of Fe; 3) both dissolved Fe and leachable particulate Fe are important for understanding Fe biogeochemistry, but information on residence time of particulate Fe is missing; 4) model parameterizations need to be improved with iron supplies from various sources; Fe removal and recycling in models need to be better described; 5) more experimental data are needed regarding physiological response of phytoplankton groups to Fe, and community structure changes to Fe supplies. Most of the presenters submitted an extended abstract before the workshop, so their key findings and recommendations on iron biogeochemistry research are expected to be summarized in WG 22's final report.

List of papers

Oral presentations

Kenneth W. Bruland (Invited)
Reactive iron in the subarctic North Pacific; natural iron enrichments

Jun Nishioka, Tsuneo Ono, Hiroaki Saito, Takeshi Nakatsuka, Shigenobu Takeda, Wm. K. Johnson and C.S. Wong
Comparison of iron distribution between the western and the eastern subarctic Pacific

Eric Roy, Mark Wells and Fei Chai
The role of Haida eddies in iron transport to the eastern subarctic Pacific Ocean

Hiroaki Saito, Kazutaka Takahashi, Yoshiko Kondo, Jun Nishioka, Tomonori Isada, Akira Kuwata, Miwa Nakamachi, Yuji Okazaki, Yugo Shimizu and Koji Suzuki
Factors controlling the spatial variability of spring bloom dynamics in the Oyashio region

Roberta C. Hamme, Sonia Batten, William Crawford, Kathleen Dohan, Steven Emerson, Karina Giesbrecht, Jim Gower, Maria Kavanaugh, Deirdre Lockwood, Christopher L. Sabine and Frank Whitney
Natural volcanic iron fertilization of the Subarctic North Pacific

Ai Hattori-Saito, Tomonori Isada, Natsuko Komazaki, Hiroshi Hattori, Kenshi Kuma, R. Michael L. McKay, Tsutomu Ikeda and Koji Suzuki
Fe nutrition in micro-sized diatoms in the Oyashio region of the NW subarctic Pacific during spring

Keisuke Uchimoto, Tomohiro Nakamura, Jun Nishioka, Humio Mitsudera, Michiyo Yamamoto-Kawai, Kazuhiro Misumi and Daisuke Tsumune
A simulation of chlorofluorocarbons in the Sea of Okhotsk

Kazuhiro Misumi, Daisuke Tsumune, Yoshikatsu Yoshida, Takeshi Yoshimura, Keisuke Uchimoto, Tomohiro Nakamura, Jun Nishioka, Humio Mitsudera, Frank O. Bryan, Keith Lindsay, J. Keith Moore and Scott C. Doney
Numerical simulation of iron export from the Sea of Okhotsk to the North Pacific

Yasuhiro Yamanaka, S. Lan Smith, Hiroshi Sumata, Naoki Yoshie, Taketo Hashioka, Takeshi Okunishi, Masahiko Shigemitsu, Maki N. Noguchi and Naosuke Okada (Invited)
New NEMURO-based model incorporating the iron cycle

Stephanie Dutkiewicz, Fanny Monteiro and Mick Follows (Invited)
Interplay between ecosystem structures and iron availability in a global marine ecosystem model

Poster

Youngju Lee and Joong Ki Choi
Effect of Asian dust on the picophytoplankton growth rate and cell cycle

Submitted and extended abstracts for the Workshop (W1) on *"Natural supplies of iron to the North Pacific and linkages between iron supply and ecosystem responses"*

* Authors shown in the above list are those who presented at the workshop.

1. Reactive iron in the subarctic North Pacific; natural iron enrichments

Kenneth W. Bruland

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E-mail: Bruland@ucsc.edu

Extended Abstract

Much of the subarctic North Pacific is an iron-limited, high-nutrient, lower-than-expected-chlorophyll (HNLC) regime. My research group has been studying the naturally occurring high-chlorophyll regions that develop at the boundaries of these Fe-limited HNLC waters and nitrate-poor, Fe-rich coastal waters. For example, we have examined the "green belt" that occurs at the shelf break in the southeastern Bering Sea (Aguilar-Islas *et al*., 2007) and the "iron curtain" hypothesis. In the summer of 2007 we carried out a major field study to test the hypothesis that regions of high biomass observed in satellite imagery in the northern Gulf of Alaska (GoA) in mid-summer are the result of the high river and glacial melt runoff during this time of year into the Alaska Coastal Current (ACC) enriching the ACC with both dissolved and leachable particulate iron, and the resultant mixing of this high iron coastal water with the HNLC waters of the adjacent GoA via mesoscale anti-cyclonic eddies. We examined the roles of Sitka and Kenai Eddies, 100 to 200 km in diameter, in transporting dissolved and leachable particulate Fe from the shelf regions offshore into the open Gulf of Alaska. Using a series of surface water transects and vertical profiles within and outside of eddies, we demonstrate the importance of eddies to the GoA region in both the current summer season and subsequent seasons. These studies provide insight into mechanisms of iron supply to this region and key biogeochemical pathways of reactive forms of iron that should be introduced in ecosystem models.

What are the gaps and issues related to experimental and modeling activities on an iron cycle study in the subarctic North Pacific?

- With respect to the atmospheric dust input to the surface ocean, one of the largest uncertainties entails the % of Fe dissolution from types of dust.

- Similarly, the extent of dissolution or biological availability of suspended particulate Fe, especially the continental source from rivers and re-suspended sediments, is a large uncertainty.
- In coastal areas with high concentrations of suspended terrigenous particles with iron coatings, the concentration of strong Fe(III)-binding organic ligands appears to control the dissolved Fe concentrations.
- The large excess of leachable particulate Fe acts as a capacitor or buffer to supply dissolved Fe to essentially titrate the strong Fe(III)-binding organic ligands.
- Leachable particulate Fe is a far more important source of iron than has been realized. An important question is the residence time of particulate Fe in the relatively long lived eddies.

Related articles

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2. Comparison of iron distribution between the western and the eastern subarctic Pacific

Jun Nishioka[1], Tsuneo Ono[2], Hiroaki Saito[3], Takeshi Nakatsuka[4], Shigenobu Takeda[5], Wm. K. Johnson[6], C.S. Wong[6]

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Extended Abstract

Atmospheric dust has been thought to be the most important source of iron (Fe) supporting annual biological production in the Western Subarctic Pacific (WSP) (*e.g*., Duce and Tindale, 1991). Our recent study clearly indicates that there is another important source of Fe for the WSP (Nishioka *et al*., 2007, 2011). We conducted direct observations in the Sea of Okhotsk and found that Fe was re-suspended from the sediments of the north-western continental shelf area. The re-suspended Fe was included into dense shelf water (DSW), which was produced by sea-ice formation at the north-western shelf, then transported to the Kuril basin by the Okhotsk Sea Intermediate Water (OSIW). The Fe-rich OSIW influenced the surrounding waters around the Kuril Strait, so that the Fe was re-distributed to a wide range of water density in the water column (from surface to deep water) due to the strong diapycnal mixing at the strait. Chemical properties of the mixed water had an influence on the North Pacific Intermediate Water (NPIW). These results clearly indicated that re-suspended sedimentary Fe is transported by ventilation processes, which are driven by sea-ice formation in the Sea of Okhotsk, and which distribute the Fe to a wide area of the intermediate layer in the WSP (Nishioka *et al*., 2007).

The Fe supply process, *i.e*., the sedimentary Fe supply from the Sea of Okhotsk, can be used to explain the difference in Fe distribution between the western and eastern subarctic Pacific (Nishioka *et al*., 2003). Vertical measurements of Fe in the WSP indicated that increased gradients in dissolved Fe concentrations with depth from subsurface to intermediate water (NPIW) were greater in the WSP relative to those of Station Papa in the eastern subarctic Pacific (ESP). Furthermore, particulate Fe concentrations are extremely high in the water column of the western region. We also found that extremely high total Fe concentrations in the surface in the WSP occurred only in subarctic water masses north of the subarctic front (SF), and that this feature was clearly separated by the SF boundary (Nishioka *et al*., 2007). Additionally, time series of Fe observations clearly show that there was temporal variability in dissolved Fe and total Fe concentrations in the WSP. A higher temporal variability was observed to be stronger in the upstream of the Oyashio flow than at the oceanic station in the downstream of the Oyashio flow and in the ESP. From the spatial and temporal Fe distributions, we determined that the high Fe input, mainly in the particulate phase, occurs north of the SF and upstream of the Oyashio region, and the Fe is subsequently distributed to the cold subarctic water in the WSP area. These time-series and spatial data also indicate that some fractions of the Fe in particulate and colloidal matters were lost from the water column during the water transportation. The results are consistent with our studies that the Fe-rich water is transported from the Sea of Okhotsk to the WSP. Therefore, the presence of Fe in the WSP cannot be solely explained by aeolian dust supplies over the study area (Nishioka *et al*., 2007).

Furthermore, we observed a clear seasonality in dissolved Fe concentrations in the surface waters of the Oyashio region (Nishioka *et al*., 2011). The Fe-rich intermediate water, also beneath the surface in the Oyashio region, influence the high concentrations of dissolved Fe in the surface layer in winter by seasonal mixing processes. The surface waters are significantly influenced by high Fe concentrations in the intermediate waters through diffusion and winter mixing. Therefore, in addition to the traditional view of dust

input, the Fe transported by intermediate waters should be considered as an important source of Fe for phytoplankton blooms in the Oyashio region and the Oyashio-Kuroshio transition zone.

Similar sedimentary Fe supply processes have already been reported in the Gulf of Alaska. Previously, Martin *et al.* (1989) reported on a North-South vertical section profile in the Gulf of Alaska, and indicated that enhanced Fe input occurred along the Alaska continental margin. Takata *et al.* (2006) also indicated that high particulate Fe levels in intermediate to deep waters observed at 50°N, 165°E may be due to the input of Fe from the Alaskan continental margin to the Alaskan Stream. Our previously observed Line P data also indicate the influence of the continental margin along Line P (Nishioka *et al*., 2001). These results are all consistent with numerical modeling studies and water current structures in the Gulf of Alaska (Lam *et al*., 2006).

The continental shelf is increasingly recognized as an important source of Fe in the many regions in the subarctic Pacific and its marginal sea (*e.g*., Johnson *et al*., 2005; Hurst and Bruland, 2007; Aguilar-islas *et al*., 2007; Nishioka *et al*., 2007). Location of the continental shelf in relation to water formation and current direction, especially in the mesopelagic layer, is an important factor for controlling the long-distance transport of sedimentary Fe into the subarctic Pacific. Therefore, in addition to the traditional view of dust input, the sedimentary Fe sources and Fe transport by the water current system, especially in the intermediate layer, should be considered as an important source of Fe for biological production in the subarctic Pacific. Quantitative evaluation of these Fe sources, with an upward transport system, can contribute to a better understanding of the mechanisms influencing biological production and Fe biogeochemical cycles in the subarctic Pacific.

Summary

- Sedimentary Fe sources are important to understand Fe biogeochemistry in the subarctic Pacific.
- These sources of Fe can explain the differences in Fe distribution and biological production between the WSP and the Station Papa.
- Location of the continental shelf in relation to water formation and current direction, especially in mesopelagic layer, is an important factor for controlling long-distance sedimentary Fe transportation in the subarctic Pacific.
- Considering this source of Fe with upward transport processes is essential in our understanding of biological production and biogeochemical cycles in the WSP and ESP.

1) What are the gaps and issues related to experimental and modeling activities?
   - Location of continental shelf with water formation and current direction, especially in the mesopelagic layer, is an important factor in controlling sedimentary Fe transportation in the subarctic Pacific. The model should include these processes with high resolution water circulation.
   - The main form of Fe, which is supplied from sedimentary sources, is in particulate form. We need to know the spatial change of the particulate Fe bio-availability which contributes to phytoplankton growth. (We need more experiments, and more observations, for evaluating its bio-availability. Models should represent particulate Fe with changing bio-availability).
2) What are the processes that can explain the upward Fe transport from the intermediate water to the surface layer (tidal mixing, winter mixing, Ekman transport, *etc.*)?
   - Modeling studies can suggest some processes.
3) What should be suggested for international research programs focusing on Fe biogeochemistry?
4) Is there any other sedimentary Fe source area and transport system to the open ocean?
   - We need other process studies.

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3. The role of Haida eddies in iron transport to the eastern subarctic Pacific Ocean

Eric Roy, **Mark Wells** and Fei Chai

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The constraint of carbon export by iron supply to the high nitrate, low chlorophyll (HNLC) subarctic Pacific likely has contributed to past global climate change. Each year, mesoscale (~100 km diameter) eddies form off the Canadian and Alaskan coasts and transport coastal waters to the open ocean. We studied the distribution of dissolved (<0.45 µm) and total iron in Canadian coastal shelf waters, in a 3 month old eddy off the Queen Charlotte Islands (Haida Gwaii), and in surrounding oceanic waters. Our measurements show that iron levels were near oceanic levels in eddy surface waters while concentrations of iron below 80 m were ten-fold higher than outside the eddy. A simple one-dimensional advective/diffusion model's estimates indicate that iron infusion to surface waters in this single eddy roughly matches the total annual dissolvable aerosol iron inputs to the entire eastern subarctic Pacific. We are analyzing the potential impact of eddies on iron transport in more detail using the Pacific Regional Ocean Model System (ROMS) model, utilizing the modeled vertical and horizontal velocities with our limited iron measurements. These estimates of vertical and horizontal iron fluxes will help better ascertain whether eddy transport mechanisms can represent a major source of Fe to this HNLC region. However, in contrast to aerosol inputs that persist or increase during periods of glaciation, the mechanisms driving eddy formation would be greatly diminished or absent during glacial low sea level stands. The reduction of these mechanisms would in turn reduce iron transport to the eastern subarctic Pacific and provide a potential negative feedback mechanism affecting global climate.

4. Factors controlling the spatial variability of spring bloom dynamics in the Oyashio region

Hiroaki Saito[1], Kazutaka Takahashi[1], Yoshiko Kondo[2], Jun Nishioka[3],Tomonori Isada[4], Akira Kuwata[1], Miwa Nakamachi[1], Yuji Okazaki[1], Yugo Shimizu[1], Koji Suzuki[4]

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The spring phytoplankton bloom is a routine event in the Oyashio region of the western subarctic Pacific. In addition to the ample supply of macro-nutrients to the euphotic zone by winter mixing, the high concentration of iron enables diatoms to utilize nitrate and that induces spring blooms. The supply of iron makes the Oyashio region different from the HNLC subarctic Pacific. The timing and magnitude of spring phytoplankton blooms are spatially heterogeneous. Satellite remote sensing clearly represents the variability in chlorophyll concentration, and the variations of environmental factors associated with the chlorophyll concentration are also detected by the monitoring study along the *A-line* across the Oyashio region. However, the time resolution (monthly to bimonthly) and the limited observational parameters in the *A-line* monitoring programme prevent further understanding of the factors controlling the phytoplankton dynamics in the Oyashio region. In order to overcome such limitations, we carried out repeated mapping observations in the Oyashio region in 2008 in the BLOSSOM (BLOoming plankton Succession Study in the Oyashio Marine ecosystem) project. Finer temporal resolution and more observational parameters than those obtained in the *A-line* monitoring revealed that light and/or iron availabilities, which were mainly determined by physical properties, would affect the spatial heterogeneity of the spring bloom dynamics in the Oyashio region.

5. Natural volcanic iron fertilization of the Subarctic North Pacific

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We present evidence of a widespread bloom in the Subarctic Pacific in August-September 2008, which may have been caused by volcanic ash input. Satellite-derived surface chlorophyll and brightness from MODIS showed the highest average values seen in this region since 1997 and showed that the phenomenon was widespread over the entire Eastern Subarctic Pacific. Two cruises to Station P (50^{o}N 145^{o}W) in late August confirmed unusually high net community production (from O_2/Ar measurements) and gross production (from short-term ^{14}C incubations). Nitrate and silicate concentrations were lower than normally observed in this HNLC region. Seawater pCO_2 and pH measured on a mooring at Station P demonstrate drawdowns in DIC and alkalinity beginning on August 13. Mesozooplankton biomass, from continuous plankton recorder surveys, was unusually high in August 2008. The timing of the beginning of this bloom event matches the unusually broad dispersal of volcanic ash from the eruption of Kasatochi in the Aleutian Islands August 7-8. Evidence from satellite altimetry and derived currents as well as the widespread nature of the bloom argues against mesoscale eddies as a cause. Although mixed layers were deeper in this region during winter of 2008, normal stratification was established by mid-June and the summer was not significantly cloudier than normal. QuikSCAT winds for the region show that August 2008 was only somewhat winder than average, suggesting that enhanced vertical mixing was not a primary driver. A large-scale iron fertilization of the region by volcanic ash remains the principal hypothesis for this event.

6. Fe nutrition in micro-sized diatoms in the Oyashio region of the NW subarctic Pacific during spring 2007

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Extended Abstract

It is hypothesized that Fe availability controls the growth of phytoplankton significantly in the Oyashio region during spring (Hattori-Saito *et al*., 2010). We examined Fe stress in micro-sized (20–200 µm) diatoms at a station in the Oyashio region during the spring bloom period from 6 April to 1 May in 2007, by immunological ferredoxin/flavodoxin assays and measuring the maximum photochemical quantum efficiency of PSII (F_v/F_m). The abundance and species composition of the diatoms were also examined concurrently with the hydrographic conditions including dissolved Fe (D-Fe) and macronutrient concentrations. Chlorophyll *a* concentrations at 5 m depth were consistently high (2–29 mg m^{-3}), indicating that phytoplankton had bloomed throughout the cruise (Isada *et al*., 2010). According to the scanning electron microscopic analyses of the diatoms collected from 5 m depth, chain-forming centric diatoms dominated the phytoplankton community throughout the cruise. Interestingly, the dominant diatoms changed from *Thalassiosira* and *Chaetoceros* species to *Chaetoceros radicans* from 25 April. Only flavodoxin, an *in situ* diagnostic marker for Fe deficiency, in the micro-sized diatoms was detected throughout the cruise. This result indicates micro-sized diatoms were stressed by Fe availability. Dissolved Fe concentrations ranged between 0.17–0.53 nM (Nakayama *et al*., 2010). Comparing the abundance of the flavodoxin to F_v/F_m, higher abundance of flavodoxin were detected between 18 and 20 April, when the F_v/F_m values were relatively low, indicating that the diatoms suffered low iron availability in their cells. Thereafter, flavodoxin levels were decreased with the increment of F_v/F_m, suggesting that diatoms might be somewhat released from iron stress. However, no significant relationships between flavodoxin abundance and dissolved Fe concentrations or F_v/F_m were found during the observation. Despite the dramatically change of F_v/F_m and flavodoxin abundance during the survey, macronutrients were replete and dissolved iron levels were relatively stable. Our results indicated that changes in photosynthetic physiology of the micro-sized diatoms were possibly caused by the difference in iron requirements among the diatom species.

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7. A simulation of chlorofluorocarbons in the Sea of Okhotsk

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Extended Abstract

Introduction

We intend to model the iron circulation in the western subarctic gyre in the Pacific in the near future. In order to model it, three steps are needed: constructing the ocean model, constructing the iron model, and combining the two models. In this study, we have constructed an ocean model as the first step for the iron modeling.

The Sea of Okhotsk is considered to be a main source region of iron to the western subarctic gyre in the Pacific (Nishioka *et al*., 2007). Within the Sea of Okhotsk, iron is transported in the intermediate layer from the northwestern shelf along Sakhalin to the Pacific. Therefore, an ocean model that can reasonably represent circulations in the intermediate layer in the Sea of Okhotsk is essential for the iron modeling in the northwestern North Pacific area.

Chlorofluorocarbons (CFCs) are inert gasses and are distributed only by advection and diffusion after they are taken into the sea at the sea surface from the atmosphere. Accordingly, models that can represent CFC distributions reasonably well may be regarded as models that can represent current fields in the intermediate and deep layers reasonably well.

Keeping these things in mind, we have performed a simulation and two numerical experiments of CFCs.

Model

The model we use is Center for Climate System Research Ocean Component Model ver. 3.4 coupled with a sea ice model (Iced-COCO). The model domain spans the northwestern North Pacific, from 136°E to 180.5°E and 39°N to 63.5°N. The horizontal resolution is 0.5°. The model is driven by daily climatology atmospheric data at the sea surface. At the lateral boundaries and grids deeper than 2000 m, temperature and salinity are restored to the WOA01. This model does not include tidal effects; diapycnal mixing by tides along the Kuril Islands is parameterized with large vertical diffusivity. CFC experiments are performed according to OCMIP-2 protocol (Dutay *et al*., 2002). At the lateral boundaries, CFCs are restored to 0.

Results

Compared with the observation by Yamamoto-Kawai *et al.* (2004), the model represents the observed features in CFC-12 distribution reasonably well (we have simulated CFC-11 and CFC-12, but in the presentation we show only the results of CFC-12). The CFC-12 concentration in the intermediate layer is higher in the Sea of Okhotsk than in the Pacific, which implies that the source region is the Sea of Okhotsk. On the 26.8 σ_θ surface, the concentration is highest around the northern and northwestern shelf. On the 27.4 σ_θ surface, it is highest around the Kuril Islands. On the vertical section along 55.5°N, which passes through the northwestern shelf, a characteristic distribution is represented. While the CFC-12 concentration is high throughout the water column around the shelf, high concentration is limited within the winter mixed layer in the eastern part. These suggest that brine rejection and tidal mixing (diapycnal mixing by tides) play an important role to transport CFC-12 into the intermediate and deep layers.

To clarify the effects of tidal mixing along the Kuril Islands and brine rejection on the distribution of CFCs, two experiments are carried out where one of the two processes is not included. The experiment without tidal mixing along the Kuril Islands is referred to as the NOtide, and that without brine rejection is referred to as the NObrine. The simulation, which includes both the tidal mixing and brine rejection, is referred to the standard experiment.

We show the difference in the CFC-12 concentration between the standard and each experiment (the standard minus each experiment) on three vertical sections: along 55.5°N, along 50°N, which is located at the southern area of the Sea of Okhotsk, and along 151°E, which passes through Bussol' Strait. In the northwestern shelf on the section of 55.5°N, the difference between the standard and the NOtide is small, and the difference between the standard and the NObrine is large, which illustrates that brine rejection is important and tidal mixing is not very important on the northwestern shelf. On the other hand, in the eastern part on the section, the CFC-12 concentration is lower in both experiments than in the standard, but different from the standard in that the NOtide is larger and more homogeneous than the NObrine. On the section of 50°N, while the difference between the standard and the NOtide is large below a depth of about 100 m independent of longitude, prominent difference between the standard and the NObrine is only along the Sakhalin in depths of a few hundreds meters, which corresponds to the path of Dense Shelf Water (DSW). On the section of 151°E, the difference is distributed similarly. The difference between the standard and the NOtide is large below a depth of about 100 m independent of latitude, and the difference between the standard and the NObrine is prominent only in depths of a few hundreds meters around the Kuril Basin, which corresponds to the path of DSW. The differences on the three vertical sections illustrate that tidal mixing along the Kuril Basin plays a great influence in the distribution of CFCs below the winter mixed layer over the entire Sea of Okhotsk while it is only along the path of DSW that brine rejection greatly influences the distribution of CFCs.

CFC cumulative flux is a time-integrated CFC flux at the surface during the simulation period, and it shows where CFCs are taken into the sea. In the simulation, the most prominent uptake of CFCs occurs around the Kuril Islands. Another prominent uptake occurs around the northwestern shelf. Those two prominent uptakes disappear in the experiments without tidal mixing along the Kuril Islands and brine rejection, respectively. Therefore uptake in those areas is due to brine rejection and tidal mixing, respectively. Those two processes make temperature and CFCs concentration low at the sea surface through convection or mixing. The lower temperature and CFCs concentration are, the more CFCs are absorbed in the sea. Therefore, the uptake of CFCs in these two areas is large. While tidal mixing exists throughout the year, brine is rejected only in winter. Hence, the uptake in the northwestern shelf is not as large as around the Kuril Islands.

Concluding remarks

The influence of tidal mixing along the Kuril Islands is very large on the distribution of CFCs over the entire Sea of Okhotsk. On the other hand, influence of brine rejection is large only in a limited area. However, in view of iron supply from the Sea of Okhotsk to the Pacific, brine rejection is, of course, important because the influence of brine rejection is large along the path of DSW, and iron is transported with DSW. In this study, we have not discussed CFCs distribution in the Pacific since the model boundaries exert great influence there. Tidal mixing is expected to exert great influence on the distribution in the Pacific; it redistributes vertically the CFCs when they pass through the Kuril Straits.

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8. New NEMURO-based model incorporating the iron cycle

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Supplies of essential micro-nutrient iron to the upper ocean largely determine regional differences in biological production in the North Pacific Ocean. The original NEMURO model developed by the PICES/GLOBEC CCCC MODEL Task Team did not include iron, so we have developed a new ecosystem model including iron cycling with the new Optimal Uptake (OU) kinetics for multiple nutrients. Smith and Yamanaka (2007) and Smith *et al*. (2009) showed that, compared to the classic Michaelis-Menten (MM) kinetics, OU kinetics better explains the observed nutrient uptakes from both laboratory and shipboard experiments. By fitting the respective versions (MM and OU kinetics) of an identical ecosystem model to the same data, Smith *et al*. (2010) have rigorously compared MM and OU kinetics in a modeling study of the SERIES iron-enrichment experiment. MM kinetics could not reproduce the observed increase in Si uptake rate as a function of the decreasing trend in concentration of silicic acid. Also, the MM kinetics predicts Si limitation throughout nearly all of the experiment after iron-fertilization. By contrast, OU kinetics reproduces the observed increase in Si uptake rate and matches the observed estimate for the timing of the return to iron limitation. Previous studies have shown that including the iron cycle (with MM kinetics) has fixed problems in models without iron (*e.g.*, overestimates of chlorophyll-*a* in the Southern Ocean and of nutrient concentration in the subarctic North Pacific). However, the inclusion of the iron cycle has degraded model performance for some regions, such as the Equatorial Pacific. We are estimating the key parameters of our model with OU kinetics for 17 sites, including JGOFS stations.

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9. Interplay between ecosystem structures and iron availability in a global marine ecosystem model

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Extended Abstract

We examine the interplay between marine ecosystem structure and iron supply in the context of a global three-dimensional ocean model where self-assembling phytoplankton communities emerge from a set of potentially viable organism types, including diazotrophs. The parameterization of the iron cycling includes representations of advection/diffusion, biological uptake, remineralization, aeolian and sedimentary sources, as well as explicit complexation with an organic ligand and scavenging (Parekh *et al*., 2005). We explore how the availability of iron critically regulates the ecosystem structure in the modeled Pacific, and how the ecosystem itself controls iron concentrations. We use resource competition theory (Tilman *et al*., 1977, 1982) to understand our results. Competition resource theory suggests a strong link between ecosystem structure and nutrient concentrations and supply. In the simplest form (see Dutkiewicz *et al*., 2009) it suggests that phytoplankton biomass is controlled by the supply of the limiting nutrient and the phytoplankton loss rates (*e.g*., grazing). In turn, the concentration of the limiting nutrient is controlled, not by the supply rate, but rather by the phytoplankton physiology and loss rates.

Firstly we explore how different assumptions about the solubility of Aeolian dust deposited iron affect the phytoplankton biomass, distribution of diazotrophs and concentration of iron. We examine simulations where we assume uniform solubility (4% and 1%) of the iron dust estimates of Luo *et al*. (2003), as well as newer estimates of spatially variable solubility (Luo *et al.*, 2008). We compare results between the different experiments. We find, as have several studies (*e.g*., Moore *et al*., 2004, Moore and Doney, 2007, Krishnamurthy *et al.*, 2009), that increased iron supply (here due to higher solubility) leads to slightly higher global primary production, and significantly higher global nitrogen fixation. Here, we concentrate on the differences in the experiments seen in the North and central Pacific.

The spatial patterns of differences of local biomass and iron between experiments are quite complicated. We find that resource competition theory does explain many of the differences:

1. Where the limiting nutrient of the dominant phytoplankton is iron, biomass increases with increasing iron solubility, but ambient iron concentrations remain fairly constant.
2. Increased nitrate consumption in these regions leads to reduced lateral supply of nitrogen to surrounding regions (*e.g*., Williams and Follows, 2003; Dutkiewicz *et al*., 2005), resulting in a decrease in biomass downstream.
3. Increased iron solubility leads to larger regions where diazotrophs can exist (though they are never dominant). Nitrogen fixation increases leads to a larger supply of nitrogen which allows a larger biomass of non-diazotrophs.

We consider two additional sensitivity experiments where we examine what happens if we “alter” the physiology of the phytoplankton, in particular we change the value of the Monod iron half saturation constant. Resource competition theory predicts accurately the altered iron concentration and also that biomass remains unaltered. In addition, we find that the region inhabited by diazotrophs changes: This too is suggested by resource competition theory (explored further in Monterio *et al.*, 2009).

From a modeling perspective these results suggest that we cannot simulate ecosystems correctly before good parameterizations of iron supply, but also we will not be able to capture iron concentrations without successfully parameterizing the ecosystem structure and physiology. More importantly however, this work helps us further our understanding of the strong coupling between ecology and nutrient cycling.

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10. Effect of Asian dust on the picophytoplankton growth rate and cell cycle

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To investigate the effect of Asian dust on picophytoplankton, we carried out laboratory experiments for the variations of growth rate and DNA cell cycle on *Prochlorococcus* and *Synechococcus* after addition of Asian dust. There are no differences in the growth rates of control samples and experimental samples with additions of 5%, 20%, 50% Asian dust, respectively. The specific growth rates of *Prochlorococcus* and *Synechococcus* in the experiment with additions of 50% Asian dust were lower than others and the additions of 20% and 50% Asian dust also induced a *Synechococcus* cell cycle response. But the 50% addition of Asian dust was a high concentration relative to the concentration in the ocean during Asian dust periods. These results indicated that a high concentration Asian dust has a physiological effect on picophytoplankton growth and cell cycle.

PICES Nineteenth Annual Meeting, PICES-2010
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REPORT OF WORKING GROUP 22 ON *IRON SUPPLY AND ITS IMPACT ON BIOGEOCHEMISTRY AND ECOSYSTEMS IN THE NORTH PACIFIC OCEAN*

The final meeting of the Working Group on *Iron Supply and its Impact on Biogeochemistry and Ecosystems in the North Pacific Ocean* (hereafter WG 22) was held from 14:00–18:00 hours on October 24, 2010. The Co-Chairmen, Drs. Fei Chai and Shigenobu Takeda, called the meeting to order and welcomed the participants (*WG 22 Endnote 1*). The draft agenda was reviewed and adopted (*WG 22 Endnote 2*). As WG 22 will be disbanded in 2010, the Co-Chairmen expressed appreciation to the WG 22 members and to all scientists who contributed to the workshop and the annual meeting session proposed by the Working Group.

AGENDA ITEM 2
Review of WG 22 activities

Iron biogeochemistry data sets in the North Pacific

Data collected by WG 22 during its term (2007–2010) include dates, position (station, depth), cruise #, iron measurements (size, analytical method). A map of the stations and a list of the data sources will be prepared. Dissolved iron data sets collected from Japanese scientists are being work on. WG 22 members (Drs. Takeda, Mark Wells and William Crawford) will contact other key scientists who have made iron measurements in the North Pacific in order to collect as much available iron data as possible. The database may include cruise/station information in which iron samples were collected and analyzed but have not been published.

Report on BIO Topic Session 2 (S2)

To review the past and ongoing laboratory, field and modeling studies on iron biogeochemistry and its impact on biological productivity and marine ecosystems in the North Pacific Ocean, WG 22 convened the BIO Topic Session co-sponsored by SOLAS (Surface Ocean-Lower Atmosphere Study) on "*Understanding the role of iron in regulating biogeochemical cycles and ecosystem structures in the North Pacific Ocean*" at the PICES-2010 in Portland, U.S.A. Participation included scientists from Canada, China, Germany, Japan, and the United States (*WG 22 Endnote 3*). There were 11 oral presentations focusing on iron biogeochemistry and the impact of iron (dust) on ecosystem dynamics, based on field observations, onboard experiments and numerical models. A summary of the session is included in the Session Summaries section of this Annual Report. Co-convenors (Drs. Angelica Peña, Toshiro Saino and Mark Wells) will ask invited speakers to submit extended abstracts with key figures and tables to be included in the WG 22 final report.

AGENDA ITEM 3
Basic questions and recommendations for the future of iron studies within PICES

The Working Group discussed basic questions regarding the future of iron studies within PICES. It was agreed that the next phase of iron research in the North Pacific will involve:

- ecosystem responses to changes in iron supply rate, amount, and pathway,
- dissolution or biological availability and residence time of suspended particulate Fe (from rivers, resuspended sediments, industrial combustion, and dust),
- mechanisms controlling chemical speciation of Fe in seawater and interaction of Fe binding organic ligands with particulate Fe,

- dynamics of Fe binding organic ligands, and
- interactions of iron with other stressors such as pH, Cu, *etc*.

For improving ecosystem models that include an iron cycle, more information is needed on:

- iron removal and recycling,
- iron sources,
- physiology of co-limitation by iron and other parameters, and
- grazing on phytoplankton communities.

The Working Group agreed that they needed to have a better understanding of the iron supply before they can get ecosystems right, but they also need to get ecosystems right before they can get the iron concentration right.

WG 22 recommended that PICES should support:

- integration of regional studies on iron biogeochemical cycles and its ecosystem impacts,
- development of a North Pacific database for iron and related parameters,
- symposium/annual meeting sessions on the role of iron in regulating ecosystem responses to natural and anthropogenic forcing in the North Pacific, and
- model inter-comparisons activities.

WG 22 term of reference 5 "*Elucidate the role of iron as a potential regulator of harmful algal bloom (HAB) in coastal ecosystems of the North Pacific*" has not been fully taken up for discussion in WG 22. Therefore, it is suggested that this topic could be incorporated into the activity plans of HAB-S and/or FUTURE.

AGENDA ITEM 4

Publication of the WG 22 final report

A draft of the final report will be prepared for the PICES Scientific Report series in April 2011. The contents and assignment of the WG 22 final report were discussed (*WG 22 Endnote 4*). WG 22 will also prepare a review to be submitted to *Oceanography* that summarizes the key issues on iron sources and cycling in the North Pacific and the Working Group recommendations for future iron studies in the North Pacific.

AGENDA ITEM 5

Future activities related to the work of WG 22

- A workshop on Asian Dust and Ocean EcoSystem (ADOES), November 28–December 2, 2010;
- A joint Quebec–Shandong provinces workshop on ocean acidification in Qingdao, December 6–8, 2010;
- American Geophysical Union 2010 Fall Meeting, December 15:
    - B06 Linkages in biogeochemical cycles between the surface ocean and lower atmosphere over the Pacific Ocean (Convenors: Mitsuo Uematsu, William Miller, and Maurice Levasseur);
    - OS27 Biological, chemical and physical controls on the Gulf of Alaska ecosystem (Convenors: John Crusius, Rob Campbell, Yi Chao, and Fei Chai);
- A SCOR Working Group 131 Synthesis and Modelling workshop (Convenors: Philip Boyd and Dorothee Bakker), Summer 2011;
- Dr. Chai introduced a new consortium of In-Situ Iron Studies (ISIS) to resolve the impact of iron fertilization on marine ecosystems, to quantify its potential for removal of atmospheric carbon dioxide, and to improve our collective understanding of the changing ocean.

Proposal for a new working group

Dr. Maurice Levasseur (Canada) prepared a proposal for a new working group on "*Sensitivity of the North Pacific to Atmospheric Iron Deposition in a Low pH Ocean*" (*WG-22 Endnote 5*). This proposal was discussed at the COVE-AP meeting on Friday, October 22, 2010 where they decided to include the topic as part of the mandate of their own Working Group proposal on "*Ecosystem response to multiple stressors.*" COVE-AP felt that the topic of Dr. Levasseur's proposal was too specialized and should be broadened to comprise other important issues that all PICES countries are interested in. WG 22 recommended that COVE-AP consider nominating a few of WG 22's current members (*e.g.*, Levasseur, Wells, Chai, or Takeda) as potential members of the new working group to reflect the activities that have been accomplished by WG 22.

WG 22 Endnote 1

WG 22 participation list

Members

Fei Chai (U.S.A., Co-Chairman)
William Crawford (Canada)
Jun Nishioka (Japan)
Hiroaki Saito (Japan)
Shigenobu Takeda (Japan, Co-Chairman)
Mark Wells (U.S.A.)

Observers

Emilie Brévière (SOLAS)
Mike Dagg (U.S.A., BIO)
Hidefumi Fujioka (Japan)
Joaquim Goes (U.S.A.)
Josiane Mélançon (Canada)
Atsushi Tsuda (Japan)

WG 22 Endnote 2

WG 22 meeting agenda

1. Adoption of agenda
2. Review of 3 years of WG 22 activities
3. Basic questions and recommendations for the future of iron studies within PICES
4. Publication of the WG 22 final report
5. Future activities related to the work of WG 22
6. Other business

WG 22 Endnote 3

Participation list for BIO Topic Session (S2) on
***"Understanding the role of iron in regulating biogeochemical cycles and ecosystem structures in the North Pacific Ocean"* (co-sponsored by SOLAS) at PICES-2010**

Emilie Brévière (Germany, SOLAS)
Fei Chai (U.S.A.)
Hong Chen (China)
William Crawford (Canada)
Jay Cullen (Canada)
Huiwang Gao (China)
Josiane Mélançon (Canada)
Kazuhiro Misumi (Japan)
Jun Nishioka (Japan)
Hiroaki Saito (Japan)
Mark Wells (U.S.A.)
Others

WG 22 Endnote 4

WG 22 final report

- Table of Contents
- Introduction (Fei, Takeda)
- Natural supplies of iron to the North Pacific
  - Atmospheric depositions, rivers and resuspended sediments (Nishioka, Wells, Crawford, Uematsu)
- Linkages between iron supply and ecosystem responses (Yamanaka, Fei)
  - Model improvements during the past three years
  - New ecosystem models with iron cycle
- Data sets of iron and related parameters in the North Pacific (Takeda, Wells)
  - Dissolved Fe, particulate Fe, total Fe, Fe(II), and organic ligands data
  - Station maps
- Basic questions and Recommendations for future activities of iron studies within PICES and connection with other international programs (Saito, Wells, Maurice, Fei, Takeda)
- References
- Appendices
  - List of iron measurements in the North Pacific,
  - Annual reports,
  - (Extended) abstracts from the workshop/session.

WG 22 Endnote 5

A proposal for a new expert group on
Sensitivity of the North Pacific to Atmospheric Iron Deposition in a Low pH Ocean

Co-Chairs (proposed)
Maurice Levasseur (Laval University, Canada)
Gui-Peng Yang (Ocean University of China, China),
Philippe Tortell (University of British Columbia, Canada)
Shigenobu Takeda (Nagasaki University, Japan)

Proposed members
Martine Lizotte (Laval University, Canada)
Guangyu Shi (Institute of Atmospheric Physics, China)
Hui-Wang Gao (Ocean Institute of China, China)
Nadja Steiner (Fisheries and Oceans Canada, Institute of Ocean Sciences)
Lisa Miller (Fisheries and Oceans Canada, Institute of Ocean Sciences)
Michael Scarratt (Fisheries and Oceans Canada, Maurice Lamontagne Institute)
Takeshi Yoshimura (CRIEPI, Japan)
Mark Wells (University of Maine)
Jay Cullen (University of Victoria, Canada)
Andrew Ross (Fisheries and Oceans Canada, Institute of Ocean Sciences)

Rationale
Twelve large-scale iron ocean fertilizations (IOFs) have been conducted so far in order to assess the impact of Fe deposition on primary production, carbon sequestration, climate-relevant trace gas emissions, and global climate (see reviews by de Barr *et al.*, 2005; Boyd *et al.*, 2007). These experiments have shown that Fe-dust can increase, albeit modestly, carbon sequestration, and significantly affect the production and flux of DMS and other trace gases to the atmosphere (see review MEPS, 2008). In several of these experiments, the dynamics of DMS were tightly coupled to the growth and decline of prymnesiophytes such as *Emiliania huxleyi* and *Phaeocystis* spp. which tended to respond quickly to iron addition. These early blooms of prymnesiophytes also contributed to carbon production and sequestration by diverting a portion of the nutrients

from the diatom blooms. Several prymnesiophytes are calicifying organisms, which are highly sensitive to variations in pH. Thus, the predicted decrease in oceanic pH could affect their response to iron availability. This could significantly alter the impact of atmospheric iron deposition on the North Pacific ecosystems.

Central Objective

To determine how the predicted decrease in ocean pH will impact the response of the HNLC ecosystems to atmospheric iron deposition in the North Pacific.

General Approaches

This important question should ideally be addressed through large-scale *in situ* experiments (addition of dust, Fe, Fe+CO_2, CO_2, control). But this represents a technical, financial, and logistical challenge probably out of reach. For this reason, we propose to start with the development of onboard and *in situ* mesocosms protocols. Such protocols should allow maintaining a constant pH level for the duration of the experiment (several days). These experiments should be conducted in the different HNLC regions. The target area for the PICES WG 22 could be the North Pacific HNLC waters.

Specific Approaches for WG 22

In Canada, part of this project could be associated with the ongoing Line P cruise program led by the Institute of Ocean Sciences (IOS) of the Department of Fisheries and Oceans (DFO). Additional days devoted to the project could be added to the two Line P summer cruises if we can find extra money (NSERC) to cover these extra days at sea. Chinese colleagues could explore the possibility of obtaining a special research permit to use Chinese dust during PICES experiments. Mesocosms have been developed for ocean pH studies by Dr. Ulf Riebesell. Dr. Levasseur contacted him for potential use of the mesocosms at OSP).

Contributions

The proposed working group would contribute to bring together the following ongoing activities, foster additional collaborations, and help secure funding; 1) In Canada, Nadja Steiner (IOS-DFO) and Maurice Levasseur (Laval University) are already leading a project on the co-effect of Fe and pH on the North-East Pacific Ecosystem, 2) Maurice Levasseur (Laval University) and Gui-Peng Yang (Ocean University of China) received funds from the Government of Quebec (Canada) to conduct a joint Quebec–Shandong workshop on the impact of ocean acidification on marine resources and biogeochemical cycles. The objective of the workshop is to establish a new Quebec–Shandong joint multidisciplinary 3-year research program on the impact of ocean acidification and the functioning of marine ecosystems, coastal resources, and biogeochemical cycles.

Related Article

Levasseur, M. 2011. If Gaia could talk. *Nature Geoscience* **4**: 251–252.

PICES Nineteenth Annual Meeting Topic Session Summary

BIO Topic Session (S2)
Understanding the role of iron in regulating biogeochemical cycles and ecosystem structures in the North Pacific Ocean

Co-sponsor: *SOLAS*
Co-Convenors: *Angelica Peña (Canada), Toshi Saito (Japan) and Mark Wells (USA)*

Background

Iron plays a key role in regulating the biogeochemical cycles of carbon and nitrogen, and pelagic ecosystem structures in the North Pacific Ocean, yet our understanding of these effects remains limited. External sources of iron, such as Asian dust, rivers, sediments, and volcanoes, supply large amounts of iron to the North Pacific, while the physical processes of upwelling, meso-scale eddies, boundary currents, and tidal mixing transport deep waters with high iron concentration to the upper ocean. Biological uptake, zooplankton grazing, re-mineralization, and iron chemistry change the forms of iron and its distribution in the North Pacific Ocean. This session invited papers that address physical, biological and chemical processes controlling iron distribution and transformation, linkages between iron and ecosystem responses, and impacts on carbon and nitrogen cycles. Of special interest were papers that combine recent progress from field observations and modeling studies that relate iron cycling to ecosystem structures and carbon fluxes in the North Pacific Ocean.

Summary of presentations

The BIO/SOLAS Topic Session was held on Tuesday, October 26, 2010 and consisted of 11 oral presentations (including 2 invited talks). About 50 persons attended the session and generated interesting discussion. The papers presented at this session covered a wide range of topics from iron chemistry, sources, and distribution and iron impacts on plankton dynamics and DMS production. The first invited talk gave an introduction to iron chemistry and presented an overview on recent progress in studying how the chemical form of iron impacts its bioavailability. The second invited talk addressed the response of the marine ecosystem to natural iron fertilization by Asian dust. Dust storms carry a large amount of aerosol particles to the ocean which substantially affects surface biological production. The remaining talks covered a wide range of topics including mechanisms controlling dissolved iron distribution, sources and transport of iron by vertical winter mixing, eddies and currents, impact of Asian dust on DMS production, the role of zooplankton in smoothing the geographical heterogeneity of primary productivity generated by iron availability and the potential of ocean fertilization to sequester carbon. In addition, an overview of the activities of the international Surface Ocean-Lower Atmosphere Study (SOLAS) project was presented, including those which plans for iron related work.

List of papers

Oral presentations

Jay T. Cullen and Maria T. Maldonado (Invited)
Iron speciation and bioavailability: Insight gained from analytical chemistry and microbial Physiology

Eric G. Roy and Mark L. Wells
Evidence for regulation of Fe(II) oxidation rates by organic complexing ligands in the Eastern Subarctic Pacific

Kazuhiro Misumi, Daisuke Tsumune, Yoshikatsu Yoshida, Takeshi Yoshimura, Keisuke Uchimoto, Tomohiro Nakamura, Jun Nishioka, Humio Mitsudera, Frank O. Bryan, Keith Lindsay, J. Keith Moore and Scott C. Doney
Mechanisms controlling dissolved iron distribution in the North Pacific: A model study

William Crawford
Advection of deep-sea and coastal water into the HNLC region of the northeast Pacific Ocean

Huiwang Gao, Xiaohong Yao, Jinhui Shi and Jianhua Qi (Invited)
Response of marine ecosystem to Asian dust fertilization from coastal sea to open ocean

Josiane Mélançon, Maurice Levasseur, Martine Lizotte, Jean-Éric Tremblay, Gui-Peng Yang, Marjolaine Blais, Guangyu Shi, Hui-Wang Gao, Michael Arychuk, Keith Johnson, Nes Sutherland, Marie Robert and Wendy Richardson
Impact of Asian dust on plankton and DMS production in the Northeast Subarctic Pacific

Jun Nishioka, Tsuneo Ono, Hiroaki Saito, Keiichiro Sakaoka and Takeshi Yoshimura
Oceanic iron supply mechanisms supporting the spring diatom bloom in the Oyashio region, western subarctic Pacific

Hiroaki Saito, Jun Nishioka, Atsushi Tsuda and Hiroaki Tatebe
The role of zooplankton in buffering geographical heterogeneity of primary productivity

Fei Chai, Peng Xiu, Huijie Xue, Lei Shi and Yi Chao
Modeling impacts of mesoscale eddies on iron cycle and biogeochemical processes in the Gulf of Alaska

Emilie Brévière
The international Surface Ocean - Lower Atmosphere Study (SOLAS) project and its midterm strategy

Hong Chen, Jianbo Han and Xiaomeng Wang
A review of the influence of ocean fertilization on marine biodiversity

Submitted Abstracts for the Topic Session (S2) on *"Understanding the role of iron in regulating biogeochemical cycles and ecosystem structures in the North Pacific Ocean"*

* Authors shown in the above list are those who presented at the Topic Session.

1. Iron speciation and bioavailability: Insight gained from analytical chemistry and microbial physiology

Jay T. Cullen and Maria T. Maldonado

School of Earth and Ocean Sciences, University of Victoria, P.O. Box 3055, STN CSC, Victoria, BC, V8W 3P6, Canada. E-mail: jcullen@uvic.ca

The marine geochemistry of Fe is inextricably linked with the cycle of growth, vertical transport and remineralization of marine microbes. The availability of Fe to vegetative cells can affect the species composition, ecological structure and productivity of the phytoplankton community. Indeed, we now recognize that phytoplankton affect: 1) the distribution of Fe through active cellular uptake and subsequent sinking of organic matter to depth, and 2) the physicochemical speciation of Fe through the production of strong complexing ligands. The marine biogeochemistry of Fe and C are thus intimately coupled, in that the supply of Fe to ocean surface waters regulates the synthesis of organic matter by phytoplankton, and, ultimately, the export of organic carbon from the surface to the ocean interior. However, our current understanding of the sources, sinks and chemical speciation of Fe, especially as it relates to bioavailability, in the upper ocean is incomplete. Here we will provide an overview of recent progress by chemists and microbial physiologists, sometimes working side by side, studying how the chemical form of Fe impacts its bioavailability. Insights provided by metal-metal interactions during microbial uptake between Fe and Cd and Fe and Cu in the North Pacific will also be summarized.

2. Evidence for regulation of Fe(II) oxidation rates by organic complexing ligands in the Eastern subarctic Pacific

Eric G. Roy and **Mark L. Wells**

School of Marine Sciences, University of Maine, Orono, ME 04469, USA. E-mail: mlwells@maine.edu

Redox cycling of iron in natural seawater is an important process that can affect iron availability to marine phytoplankton, but one that often is overlooked in modelling iron effects on ocean ecosystems. We used luminol chemiluminescence to measure picomolar Fe(II) oxidation rates in continental shelf waters and surface (upper 200 m) waters of the iron-limited eastern subarctic Pacific. In both cases, Fe(II) oxidation rates were markedly faster in waters from the surface mixed layer and chlorophyll maximum depth than rates measured in UV oxidized seawater (UVOS). Conversely, Fe(II) oxidation rates measured in waters from below the mixed layer agreed well with UVOS rates. Even so, Fe(II) oxidation rates in surface and chlorophyll maximum waters slowed to converge with UVOS rates with stepwise Fe(II) and Fe(III) additions. These Fe titrations did not affect Fe(II) oxidation rates in waters from below the mixed layer. We hypothesize that excess concentrations of strong Fe(III)-complexing organic ligands known to occur in seawater accelerate Fe(II) oxidation at the surface and chlorophyll maximum; a process that we titrated away with stepwise Fe additions. Given that Fe(II) oxidation rates were enhanced only in the surface mixed layer, our findings suggest that the chemical nature, biological availability, and perhaps origin of natural Fe(III)-complexing organic ligands may differ in surface and deep waters.

3. Mechanisms controlling dissolved iron distribution in the North Pacific: A model study

Kazuhiro Misumi[1,3], Daisuke Tsumune[1], Yoshikatsu Yoshida[1], Takeshi Yoshimura[1], Keisuke Uchimoto[2], Tomohiro Nakamura[2], Jun Nishioka[2], Humio Mitsudera[2], Frank O. Bryan[3], Keith Lindsay[3], J. Keith Moore[4] and Scott C. Doney[5]

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[2] Pan-Okhotsk Research Center, Institute of Low Temperature Science, Hokkaido University, Sapporo, Hokkaido, Japan

[3] Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, CO, USA

[4] Department of Earth System Science, University of California at Irvine, Irvine, CA, USA

[5] Department of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Woods Hole, MA, USA

Mechanisms controlling dissolved iron distribution in the North Pacific are examined by numerical simulation. We use the Biogeochemical Elemental Cycling (BEC) model with the resolution of roughly 1° in horizontal directions and 60 vertical levels. The model reproduces well the iron distribution in available field data: the surface concentrations are broadly below 0.2 nM; the concentrations increase with depth; and those in the lower thermocline are especially high in the northwestern region and off the coast of California. Furthermore, the simulated result corresponds well to observed sections. Experiments changing scavenging regimes and external iron sources reveal that lateral transport of sedimentary iron into the open ocean causes the high concentrations in the northwestern region and off the coast of California. The penetration only appears under a scavenging regime where iron has a relatively long residence time at high concentrations, namely, the order of years. Sedimentary iron is intensively supplied around continental margins, resulting in locally high concentrations; the residence time with respect to scavenging determines the horizontal scale for plumes of elevated sedimentary iron. Budget analysis for iron reveals that the existence of offshore directed currents is essential for sedimentary iron transport to the open ocean.

4. Advection of deep-sea and coastal water into the HNLC region of the northeast Pacific Ocean

William R. Crawford

Fisheries and Oceans Canada, Institute of Ocean Sciences, 9860 W. Saanich Rd., P.O. Box 6000, Sidney, BC, V8L 4B2, Canada. E-mail: bill.crawford@dfo-mpo.gc.ca

Much of the northeast Pacific Ocean is labeled high-nutrient (nitrate), low-chlorophyll (HNLC) based on years of sampling of ocean-surface nutrients by research vessels. Year-to-year changes in the shape and extent of this region are difficult to track, since there are few wide-area, ship-based surveys to sample nutrients over the region. It is now possible to track the movement of different water masses based on ocean-surface chlorophyll measured from satellite and on changes in currents determined by satellite-altimetry and Argo profilers. I will combine these measurements with ship-based sampling to reveal changes in the HNLC domain over the past decade.

5. Response of marine ecosystem to Asian dust fertilization from coastal sea to open ocean

Huiwang Gao, Xiaohong Yao, Jinhui Shi and Jianhua Qi

Key Laboratory of Marine Environment and Ecology (Ocean University of China), Ministry of Education, Qingdao, 266100, PR China. E-mail: hwgao@ouc.edu.cn

Dust storm carries a large amount of aerosol particles, sweeps continents and exports to oceans. When these aerosol particles deposit in ocean, which provides abundant nutrients such as nitrogen and iron for ocean ecosystem, increases the primary production and induces algae bloom. Asian dust storm generates at a high latitude and a high elevation and is obvious a hemispheric scale phenomenon. Asian dust is unique not only in morphology, soil texture, and dust storm activities, but also mixing and capturing anthropogenic air pollutants on the transport pathway. Deposition of Asian dust substantially affects surface biological productivity. To improve understandings of Asian dust and its effect on ocean ecosystem from the coastal sea to open ocean, ADOES (Asian Dust and Ocean EcoSystem) was proposed under the frame of international SOLAS (Surface Ocean-Lower Atmosphere Study). A series of studies were performed in high-nutrient low-chlorophyll (HNLC), low-nutrient low-chlorophyll (LNLC) and eutrophication coastal regions of the Pacific Ocean. These studies provided evidence of biotic response to natural iron fertilization caused by Asian dust particles in the

subarctic North Pacific and showed that dust storm episodes were significant in the initiation of spring blooms in the East China Sea. On-board incubations on the cruise in a LNLC region of the western Pacific at the southeast of Japan showed different responses of ocean ecosystem to nitrogen and dust fertilization. Correlation of the Asian dust storms with chlorophyll, primary productivity and algae blooms in the coastal seas of China from 1998 to 2008 were illustrated.

6. Impact of Asian dust on plankton and DMS production in the Northeast Subarctic Pacific

Josiane Mélançon[1], Maurice Levasseur[1], Martine Lizotte[1], Jean-Éric Tremblay[1], Gui-Peng Yang[2], Marjolaine Blais[1], Guangyu Shi[3], Huiwang Gao[2], Michael Arychuk[4], Keith Johnson[4], Nes Sutherland[4], Marie Robert[4] and Wendy Richardson[4]

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The Alaskan Gyre is a High Nutrient Low Chlorophyll region (HNLC) characterized in summer by exceptionally high concentrations of dimethylsulfide (DMS), a biogenic gas with a potential cooling effect on climate. Surface waters in this region are sporadically replenished with Fe by aeolian dust wet deposition, events which can results in natural blooms. During the June 2009 and 2010 Line P cruises we conducted a series of onboard incubation experiments where surface water collected along Line P were enriched with dust samples from different Asian sources. Dust samples were added at concentrations of 0.12mg/L, 0.5mg/L and 2mg/L in 5L incubation bags. The incubations lasted between 48h and 96 h and the following variables were measured at T0, T24, T48 and T96: dissolved Fe, macronutrients, primary production, nitrogen fixation, chlorophyll *a*, phytoplankton and bacterial abundance, dimethylsulfoniopropionate (DMSP) and dimethylsulfide (DMS). Preliminary results will be presented and discussed in the context of reported impact of natural dust storm and artificial large scale fertilization experiments.

7. Oceanic iron supply mechanisms supporting the spring diatom bloom in the Oyashio region, western subarctic Pacific

Jun Nishioka[1], Tsuneo Ono[2], Hiroaki Saito[3], Keiichiro Sakaoka[4] and Takeshi Yoshimura[5]

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[4] Faculty of Fisheries Science, Hokkaido University, Hakodate, Hokkaido, 041-0861, Japan
[5] Central Research Institute of Electric Power Industry, Abiko, Chiba, 270-1194 Japan

Multi-year (2003-2008) time series observations along the A-line provided information on the temporal variability of the dissolved iron (diss-Fe) concentration in the Oyashio region of the western subarctic Pacific and the data indicate that an annual cycle of surface diss-Fe occurs every year. Diss-Fe was supplied into the surface water in this region every winter and supports the spring phytoplankton bloom after development of the thermocline. The diss-Fe concentration was drawn down during the phytoplankton bloom period, and was depleted in summer in some water masses. Then diss-Fe increased from autumn to winter with the increasing depth of the surface mixed layer. The high diss-Fe concentrations in the surface layer in winter were controlled by mesoscale oceanic intrinsic processes, such as vertical winter mixing and horizontal Fe-rich intermediate water transport. Difference in magnitude of the winter mixing processes among different water masses caused the heterogeneous distribution of diss-Fe concentration in the surface layer. Substantially higher diss-Fe/NO_3 ratio in the winter surface layer region has a high potential to stimulate phytoplankton growth caused by the high Fe availability allowing high potential of macro-nutrients utilization. Dust events were rare in the period when the surface diss-Fe concentration increased, therefore, the consistently occurring spring diatom blooms in the Oyashio region are concluded to be fuelled by the oceanic Fe supply.

8. The role of zooplankton in buffering geographical heterogeneity of primary productivity

Hiroaki Saito[1], Jun Nishioka[2], Atsushi Tsuda[3] and Hiroaki Tatebe[4]

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[4] Research Institute for Global Change, JAMSTEC, 3173-25 Showa-machi, Kanazawa-ku, Yokohama, 236-0001, Japan

Iron is the most essential factor controlling the ecosystems structure and dynamics of the subarctic North Pacific (SNP). Iron limitation prevents nitrate uptake of phytoplankton in most oceanic regions of the SNP and maintains the nitrate concentration high. Eastward decrease in iron supply brings the contrast of the nitrate drawdown and phytoplankton composition between eastern and western subarctic gyres. In iron-replete regions, such as the Oyashio region, centric diatoms consume nitrate and form extensive bloom in spring. In spite of large regional differences in phytoplankton biomass and composition, regional difference in zooplankton composition is less distinct. Large calanoid copepods *Neocalanus* spp., *Eucalanus bungii* and *Metridia pacifica* are dominant throughout the SNP. Recent studies on the transportation of *Neocalanus* showed that a significant fraction of the population in a oceanic domain was passively transported to other ocean domains within a generation. This suggests zooplankton with long life cycle (months – 2 years) transfer primary production to higher trophic levels after smoothing the geographical heterogeneity of primary productivity. We will discuss the relationship between iron supply, passive transportation of zooplankton and biogeography of higher trophic levels.

9. Modeling impacts of mesoscale eddies on iron cycle and biogeochemical processes in the Gulf of Alaska

Fei Chai[1], Peng Xiu[1], Huijie Xue[1], Lei Shi[1] and Yi Chao[2]

[1] School of Marine Sciences, University of Maine, Orono, ME, USA. E-mail: fchai@maine.edu
[2] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Numerous mesoscale eddies occur each year in the Gulf of Alaska, but their statistical characteristics and impact on biogeochemical cycles have never been substantially investigated. A Pacific basin-wide three-dimensional coupled physical-biogeochemical model has been developed and the results for the Gulf of Alaska are used to quantify the eddy activities and the subsequent biogeochemical responses during the period of 1993-2009. Based on sea level anomaly (SLA), the Okubo-Weiss method is used to identify eddies and a connectivity algorithm is used to track eddies in this study. In order to evaluate the model performance, the modeled results are compared with the satellite derived SLA. The impacts of mesoscale eddies to the biogeochemical processes are evaluated with the model results. The iron transport from the coast to the Gulf will be estimated with the model results. The total nitrate and silicate uptake within the eddies each year are calculated. This study suggests that mesoscale eddies in the Gulf of Alaska are important sources of iron to the euphotic zone, which plays a significant role in regulating the biogeochemical cycle in the Gulf of Alaska.

10. The international Surface Ocean - Lower Atmosphere Study (SOLAS) project and its mid-term strategy

Emilie Brévière

SOLAS International Project Office, Chemische Ozeanographie, Leibniz-Institut für Meereswissenschaften (IFM-GEOMAR), Duesternbrooker Weg 20, 24105, Kiel, Germany. E-mail: ebreviere@ifm-geomar.de

The Surface Ocean - Lower Atmosphere Study (SOLAS) project is an international research initiative focusing on biogeochemical interactions at the air-sea interface and the immediately adjacent marine and atmospheric boundary layers. It is a co-sponsored project of SCOR (Scientific Committee on Oceanic Research), IGBP (International Geosphere-Biosphere Programme), WCRP (World Climate Research Programme) and iCACGP (Commission for Atmospheric Chemistry and Global Pollution), comprising over 1600 scientists in 25 countries. SOLAS science has developed and matured considerably since publication of its Science Plan and Implementation Strategy in 2004 and there have been a number of broad-based national SOLAS research programs and related projects. In 2008, pressing scientific issues and areas where progress can be accelerated significantly with the support of SOLAS were identified and referred to as the SOLAS mid-term strategy. These topics will be presented including the topic “Atmospheric control of nutrient cycling and production in the surface ocean” under which plans for iron-related work are being developed.

11. A review of the influence of ocean fertilization on marine biodiversity

Hong Chen, Jianbo Han and Xiaomeng Wang

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Ocean fertilization may offer a potential strategy for removing CO_2 from the atmosphere by stimulating the growth of phytoplankton and thereby sequestering CO_2 in the form of particulate organic carbon. Scientific studies into the potential mechanisms for global climate modulation involving ocean fertilization activities have consistently demonstrated the stimulation of phytoplankton biomass through the addition of macro or micro nutrients in certain nutrient-deficient areas of the oceans. However, an incomplete understanding of the linkages and drivers within this complex system introduces uncertainty in the extrapolation of experimental observations to the temporal and spatial scales proposed for carbon sequestration by commercial ocean fertilization. Based on available information, four key factors limiting research on ocean fertilization are highlighted in this review: 1) a dearth of baseline information in the areas suitable for fertilization restrict the accurate observation and monitoring of impacts to marine biodiversity resulting from the alteration of chemical and biological processes; 2) the influence of natural variability and fluctuations in biogeochemical processes within the oceans on sequestration efficiency is not clear; 3) the costs, benefits and shortcomings of ocean fertilization cannot be accurately assessed; and 4) ocean fertilization, even carried out as legitimate scientific research, presents serious challenges for the law of the sea.

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Front cover figure

Location of the sampling stations compiled in PICES WG 22's dissolved iron data set of the North Pacific Ocean.