IMPORTANCE OF TIDAL MIXING PROCESS AT KRUIS STRAIT FOR IRON SUPPLY TO WESTERN SUBARCTIC PACIFIC, OYASHIO REGION

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ABSTRACT

Vertical iron distributions were investigated on the cruise around the Kruil Straits in 2006 summer, (kh06-cruise). Detailed profiles from Kruil Strait suggests that the iron-rich Okhotsk Sea intermediate waters (OSIW) influence the surface layer around the Kruil Straits and the iron was re-distributed to the wide range of density in the water column, probably due to the strong diapicnal mixing affects the chemical properties of the OSIW. This process raises the surface iron concentrations with macro-nutrients concentrations, and the water will be subsequent transported to the Oyashio region. The significantly higher ratios of iron to nitrate in mixed layer in the Kuril Strait than eastern subarctic Pacific (ESP) were observed in this study. A greater supply of macro-nutrients and substantially higher seasonal nutrient utilization in the Oyashio region, compared with ESP, might partially be explained by a larger upward iron flux in the Kruis Strait. The consideration of mixing process with re-distribution of macro- and micro-nutrient at the Kruil Strait is essential in our understanding of the biological production and biogeochemical cycles in the Oyashio region of the WSP.

1. INTRODUCTION

Resent study clearly indicated that iron limits phytoplankton growth, especially during the summer, in the western and eastern subarctic Pacific [Tsuda et al., 2003; Boyd et al., 2004]. The eastern subarctic Pacific (ESP) oceanic time series station showed little seasonal variation in phytoplankton increase [Boyd and Harrison, 1999]. In contrast, the western subarctic Pacific (WSP) is often more productive in its lower trophic levels, especially during the bloom season from spring to summer in the Oyashio region [Saito et al., 2002]. A very large biological drawdown of *pCO2* in the WSP was also observed during this period [Takahashi et al., 2002]. Since iron limits phytoplankton growth during the summer in the WSP, there are considerable interests in determining the source and seasonal timing of iron input, which can lead to a steady spring phytoplankton bloom as found in the Oyashio region.

Nakatsuka et al., [2002; 2004] pointed out that, in the Sea of Okhotsk, there is an efficient system of sediment material transport from the north-western continental shelf to the open sea via intermediate water transportation (DSW, OSIW), the ventilation processes.

Other studies also found that injections of large amounts of POC and DOC from the Sea of Okhotsk led to increase DOC concentrations in the NPIW [Hansell et al., 2002; Hernes and Benner, 2002]. Additionally Nishioka et al., [2007] and Nakatsuka et al., [2007] indicated that the intermediate waters in the WSP receive their primary source of iron through the ventilation processes originating in the Sea of Okhotsk. This source of iron is distributed to subarctic waters in the WSP area, and the form of the introduced iron is mainly in the particulate phase. However, the mixing process of the iron-rich intermediate water to surface of subarctic water in WSP have not completely understood yet.

Many previous studies clearly indicated that strong vertical mixing occurs around the Kuril Straits. The diapicnal mixing around Kruil Straits strongly affects the temperature and salinity properties of the OSIW [Tally et al., 1991; Wong et al., 1998; Yamamoto et al., 2002]. Nakamura and Awaji [2004] performed numerical experiments to study tidally generated internal waves in the Kruil Straits and showed that tidal mixing was able to reach down to the OSIW. Furthermore, surface winter turbulent and mixing is stronger and deeper in the WSP than ESP, especially Oyashio - Kuroshio inter-frontal region [eg. Suga et al., 2004]. Surface water properties in the Oyashio region is obviously influenced deeper layer water properties by the mixing processes.

Extrapolating from these previous studies, there is a possibility that the iron-rich intermediate waters may influence the surface layer around the Kruil Straits, and thus raise the surface and subsurface iron concentrations in the Oyashio region with subsequent transport and winter mixing. In this study, we investigate oceanic surface and deep iron distributions at the Kruil Strait. Then, we argue for the possibility of the influence of this source of iron on the spring bloom in the Oyashio region and biogeochemistry of WSP, which is one of the highest biological productive areas in the world oceans.

2. METHODS

2.1. Observations around the Kuril Islands

Seawater sampling was conducted from the *R/V Kromov* to observe vertical distributions of iron in the *Bussol* Strait, one of deepest strait in the Kruil Strait, in 2006 summer. The observation stations are indicated in Figure 1. To characterize vertical profiles of iron concentration, seawater samples and hydrographic data were collected using a clean CTD-carousel multiple sampler (CMS) system which housed twelve acid cleaned Teflon coated 10-L Niskin-X bottles. For sub-sampling from the Niskin-X sampler, 0.22 μm Durapore filters (Millipac 100, Millipore Corp.) were connected to the Niskin-X spigot, and the filtrate was collected in acid-cleaned 125-ml LDPE bottles (Nalgene Co., Ltd) under gravity pressure. The filtrate and unfiltered samples were used for iron measurement at onshore laboratory. Nutrients concentrations were also analysed in water samples collected from the same stations.

2.2. Iron measurement

The unfiltered the filtrate samples were adjusted to pH <1.8 with addition of 0.05 M of HCl, and the these samples were adjusted to pH 3.2 with addition of 2.4 M ammonium -10 M formic buffer and ammonium solution just before analysis. Our defined "dissolved iron" concentrations (that is, leachable iron in 0.22 Mm filtrate at pH 1.8) and "total iron" concentrations (that is, dissolved plus leachable iron in unfiltered sample at < pH 1.8) were measured by FIA chemiluminescence detection system (Obata et al., 1993). All sample treatments were performed in a laminar flow clean-air hood in a clean-air laboratory. Nutrients and chlorophyll a concentrations were also analysed for water samples. Hydrographyic data was also collected at all stations using a CTD.

3. RESULTS AND DISCUSSION

Nishioka et al. [2007] reported that changes in dissolved iron, nitrate, surface mixed layer depths (MLD) and chlorophyll a, in the surface of the Oyashio region (Figure 2, cited by Nishioka et al., 2007). They found that Oyashio region has clear seasonal variability of dissolved iron concentrations in the surface mixed layer along the monitoring line A-line. High nutrient levels in the surface mixed layer occurred in winter (~ 25 μM nitrate), due to the deep vertical mixing (~ 200 m) in winter, which delivered high nutrient subsurface water into the surface. In spring, thickness of the surface mixed layer decreased and the nitrate concentration was drawn down to 2 ~ 10 μM nitrate due to biological uptake in spring bloom. The seasonal changes in dissolved iron level was similar to that of nitrate in the surface mixed layer. The dissolved iron concentration observed in the surface mixed layer of the Oyashio region reached a maximum in January, and kept high throughout winter (ave. 0.6 nM). As the development of the spring diatom blooms, the dissolved iron levels decreased to < 0.2 nM.

The relatively high dissolved iron levels in the surface mixed layer in winter season, before the phytoplankton bloom, in the Oyashio region can be explained by three possible sources: 1) input of soluble aerosol iron, 2) turbulent vertical winter mixing of dissolved iron from the subsurface layer and 3) tidal mixing at Kruil Strait and lateral transport into the surface layer. Regarding 1), the observed frequencies of dust events in 2003 were 0 both in January and February, 6 in March, 7 in April and 2 in May [Japan meteorogical agency]. The monthly variation of the dust events was clearly inconsistent with the seasonal change in dissolved iron in the surface mixed layer of the Oyashio region in 2003. Hence, the aeolian dust input would be a minor process for the phenomenon. As for 2), Nishioka et al., [2007] indicated that their time series data can support the importance of the upward flux of iron by deep winter mixing in this region. One of the proof or evidence for this is that the seasonal change in dissolved iron behaves similar to that of nitrate in the surface mixed layer.

In this paper, we mainly focus on to Regarding 3). Total and dissolved iron concentrations at the Bussol strait were measured, and vertical profiles of iron are shown in Figure 3. The water temperature and salinity profiles on the Bussol Strait showed well mixed distributions from surface to intermediate layer (~ 600 m). The dissolved iron concentrations in the well mixed water, from surface to intermediate waters, are obviously higher than that found in the surface water in the WSP and the Oyashio region (~ 0.6 nM) [Nishioka et al., 2007] (Figure 2). Previous studies clearly indicated that strong vertical mixing occurs around the Kuril Straits. The diapicnal mixing around Kruil Straits strongly affects the temperature and salinity properties of the OSIW [Tally et al., 1991; Wong et al., 1998; Yamamoto et al., 2002]. Nakamura and Awaji [2004] performed numerical experiments to study tidally generated internal waves in the Kruil Straits and showed that tidal mixing was able to reach down to the OSIW. These detailed iron profiles from the Bussol Strait suggests that the iron-rich Okhotsk Sea intermediate waters (OSIW) influence the surface layer around the Kruil Straits and the iron was re-distributed to the wide range of density in the water column, probably due to the strong diapicnal mixing affects the chemical properties of the OSIW. It has been reported that the Oyashio region waters originate partly from Sea of Okhotsk water with 26.6-27.5 $\sigma\theta$ [Yasuda et al., 2001] and that this density range also corresponds to the iron-rich intermediate waters (NPIW) in the Oyashio region and the other region of the WSP. Therefore, the mixing process at Kruil Strait raises the surface iron concentrations with macro-nutrients concentrations, and the water will be subsequent affected to the Oyashio region.

The dissolved iron to nitrate ratio in the well mixed water in the Bussol Strait are summarized with the ratio in the waters of the Oyashio region, the WSP and the ESP in Table 1. The ESP consistently contains 0.004 nM Fe/µM NO3 in the subsurface gradient. On the other hand, the well mixed water in the Bussol Strait have similar order of number (ave 0.036 ~ 0.073, respectively) to the subsurface water of the Oyashio and the WSP (ave 0.044, 0.052, respectively), and have significantly higher ratios than ESP (0.0004) (Table 1). The consideration of mixing process with re-distribution of macro- and micro-nutrient at the Kruil Strait is probably essential for explain the higher iron to nitrate ratio in the subsurface water of the Oyashio region and WSP. Thus, winter vertical mixing in the Oyashio region and the WSP supplies more iron than in the ESP. A greater supply of macronutrients and substantially higher seasonal nutrient utilization in the WSP and Oyashio region [Tsurushima et al., 2002; Harrison et al., 2004], compared with ESP, could be explained by a larger upward iron flux in the WSP and Oyashio regions. Thus, the mixing process with re-distribution of macro- and micro-nutrient at the Kruil Strait and subsequent water transportation is probably one of important process for explain higher biological nitrate utilization and steady increases in phytoplankton biomass in the Oyashio regions.

4. CONCLUSION

We reported vertical iron profiles in the Bussol Strait and discussed importance of the mixing processes at Kruil Strait for distribution of micro- and macro-nutrient in the Oyashio and WSP water. The process can explain the high dissolved iron to nitrate ratio in the WSP and the Oyashio region, which lead higher biological nitrate utilization. Our findings contribute to a better understanding of the mechanisms influencing biological production and biogeochemical cycles in the subarctic Pacific.

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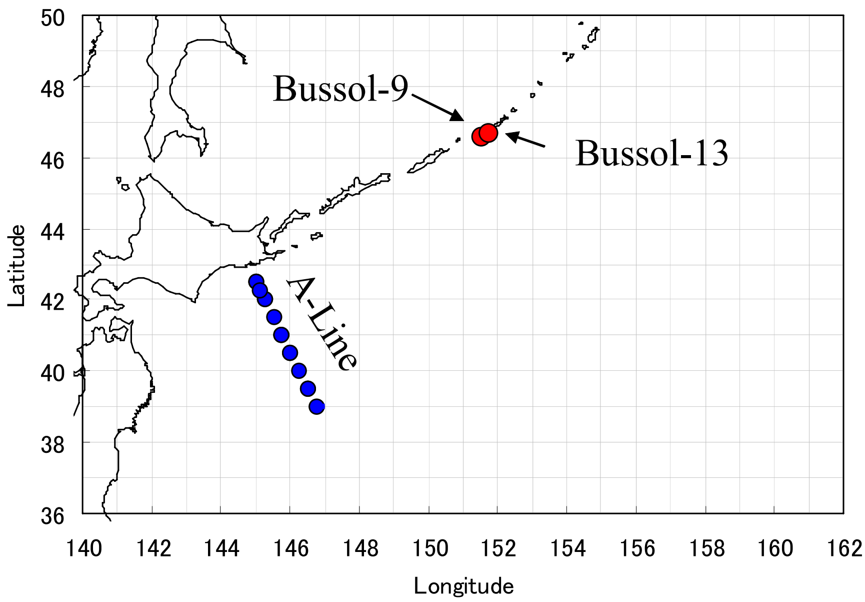

Figure 1. Chart of the western subarctic Pacific area with sampling locations in this study. Stations at the Bussol strait indicated by filled red circles are observed total iron an dissolved iron concentrations in August, 2006. Time-series observations were conducted by Nishioka et al. [2007] from January to the end of May in 2003 at stations along "A-line".

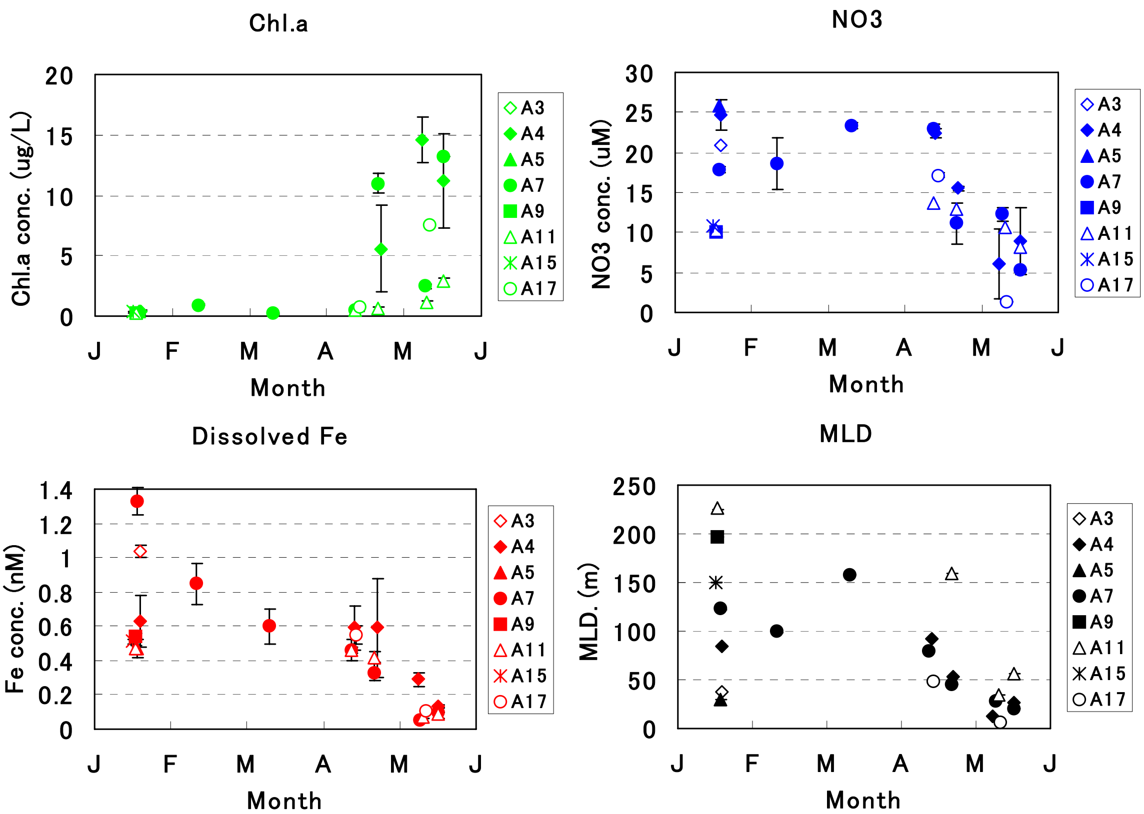

Figure 2. Seasonal variations in sea-surface dissolved iron concentrations, nitrate+nitrite concentrations, and chlorophyll a concentrations, and surface mixed layer depth from January to the end of May, 2003, along the "A-line" (After Nishioka et al., 2007)

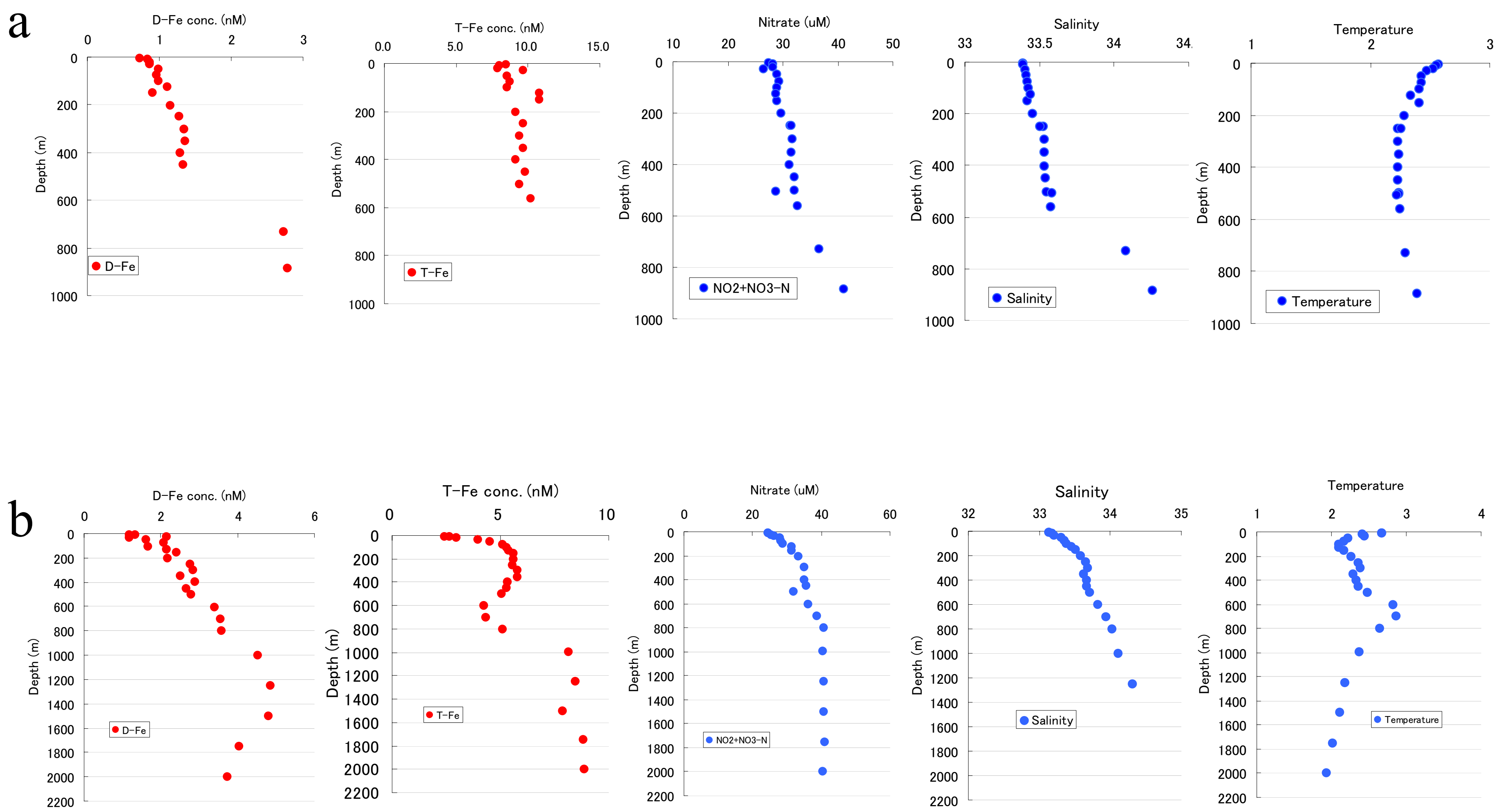

Figure 3. Vertical profiles of Dissolved iron (D-Fe), Total iron (T-Fe), Nitrate + Nitrite, Salinity and Temperature at Bussol Strait (a;Bussol-13, b:Bussol 9).

Table 1

Dissolved iron to nitrate ratio in the water of western and eastern subarctic Pacific

Water	Ave. D-Fe conc. (nM)	Ave. Nitrate+Nitrate conc. (μM)	D-Fe/N ratio
Mixed water at Bussol-9	2.35 ±0.74	31.4±5.0	0.073±0.015
Mixed water at Bussol-13	1.06±0.21	29.5±1.8	0.036±0.005
Dense Shelf Water	5.23±0.88	27.4±0.74	0.19±0.03
Intermediate water in the Oyashio	1.28±0.34	41.8±4.2	0.023±0.015
North Pacific Intermediate Wwater	1.10±0.20	40.6±2.8	0.027±0.004
Subsurface water at Oyashio	caluculated from subsurface gradient, Nishioka et al., 2007		0.044
Subsurface water at WSP	caluculated from subsurface gradient, Nishioka et al., 2007		0.052
Winter mixed layer in the Oyashio	0.85±0.12	18.6±3.2	0.048±0.12
Subsurface water at ESP	caluculated from subsurface gradient, Nishioka et al., 2007		0.004

D-Fe: dissolved iron, WSP: western subarctic Pacific, ESP: eastern subarctic Pacific