Chapter 6

Environmental Problems in the Pan Okhotsk Region

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INTRODUCTION: PAN-OKHOTSK RESEARCH CENTER

"The Pan-Okhotsk region," as termed here, includes not only the Sea of Okhotsk but also Siberia to the west, the North Pacific to the east, the Arctic region to the north, and subtropics to the south; the Sea of Okhotsk is located at a crossroad of these peculiar climatic zones. The Sea of Okhotsk is known as the southernmost sea in the northern hemisphere, where sea ice is present in winter. Its coverage is likely to be sensitive to climate changes and global warming (Nakanowatari et al., 2007). Furthermore, the sea ice variation in turn causes drastic changes in the air-sea interaction over the Sea of Okhotsk, which possibly forces anomalous atmospheric circulation in the northern hemisphere (Honda et al., 1999). The sea-ice changes may also provoke changes in material cycles and ecosystems in the region, which may produce a considerable impact on fisheries resources and products (Ono et al., 2002).

In order to foster further development of the environmental research of this region, the Pan-Okhotsk Research Center was established in April 2004 and attached to the Institute of Low Temperature Science. The goal of this center is to accurately assess the roles of the Pan-Okhotsk area in global environmental changes as well as to assess the impacts of global changes on the area. In order to accomplish this goal, we are fully utilizing our strength in field experiments, long-term monitoring, and modeling to investigate the Pan-Okhotsk area, where data are still sparse. This center is also expected to play a central role in the international research community.

In this article, we discuss the impact of global warming on the Pan Okhotsk environment, to which we are giving particular attention as an activity of the center.

IMPACT OF GLOBAL WARMING AND SEA ICE VARIATION

The Sea of Okhotsk is covered by sea ice in winter because the coldest region in the Northern Hemisphere is upstream in Siberia. The average temperature is below –40℃ in mid-winter. A cold and dry northwesterly wind blows from this region to the ocean associated with the East Asian Monsoon. The Siberian High is a primary factor that controls the monsoon in this region (Takaya et al., 2007). This cold and dry wind freezes the Sea of Okhotsk in such low latitudes.

The sea ice formation in the Sea of Okhotsk has two mechanisms. One is the ice formation in mid-ocean. The surface layer of the Sea of Okhotsk is covered by fresh water due to discharge from the Amur River, excess precipitation relative to evaporation, and sea ice melting. The fresh water layer makes a strong halocline at a depth of about 100m. The winter convection occurs within this thin surface layer, and, hence, the surface layer can quickly cool down to freezing.

The second mechanism of sea ice formation occurs over the shallow continental shelf along the northwestern coastal area. Since the sea is shallow, the water temperature can quickly cool down to freezing. Furthermore, another important factor important for efficient ice production is the northwesterly monsoon wind from the continent. Since the monsoon wind blows dominantly in the offshore direction, sea ice is carried away offshore continuously, and, therefore, the waters tend to be always open adjacent to the coast, where the ice is constantly produced. This open water is called a polynya. In the case of the Sea of Okhotsk, because of the dominant northwesterly monsoon wind, a polynya is frequently formed along the northwestern shelf. It is estimated that the total production there would be sufficient to cover the entire Sea of Okhotsk. Therefore, the northwestern polynya is considered to be an ice factory of the sea (Ohshima et al., 2007).

There are clear indications of global warming around the Sea of Okhotsk. First of all, the Siberian High in late fall and winter has been weakened for the last 30 years. Temperature increases almost 5℃ in the northeastern Eurasian Continent during this period. Associated with this warming, sea ice production and the coverage in the Sea of Okhotsk seem to be decreasing recently (Nakanowatari et al., 2007). There are perhaps three effects that influence sea ice variation when the Siberian High becomes less active:

(1) Because of a weaker heat flux over the northern shelf polynya due to increases in the air temperature, ice production becomes less active.

(2) The weak Siberian High implies a relatively strong Aleutian Low, which tends to change the wind direction from the offshore direction to the longshore direction. The latter is not favorable for the polynya opening, and, hence, sea ice production may decrease.

(3) Open ocean ice production tends to be suppressed because of a weaker heat flux. Furthermore, warm sea surface temperatures also enhance the ice melt when the sea ice drifts to the open ocean. This suppresses the extension of the sea ice coverage.

All of these effects are probably important for the recent decrease of the sea ice extent, although we have not yet identified the relative importance of each effect.

DENSE WATER FORMATION AND INTERMEDIATE LAYER CIRCULATION IN THE PAN OKHOTSK REGION

It is suggested that there would be various consequences of a reduction in the amount of sea ice in the Okhotsk Sea. For example, the intermediate layer circulation in the Sea of Okhotsk and Western subarctic Pacific (WSP) will be affected, which is of particular concern to us.

The intermediate level (200–800m) of the North Pacific Ocean is occupied by salinity minimum water, known as the North Pacific Intermediate Water (NPIW). Recent studies have clarified that NPIW originates from the northern shelf of the Sea of Okhotsk, where polynya forms and ice production is vigorous (Mitsudera and Nakamura, 2007, as a review). The water produced there is called dense shelf water (DSW). DSW is formed when sea ice is produced. In other words, when the salty water freezes and ice forms, concentrated salty water, called brine, is rejected from the sea ice because ice is made of fresh water. The brine settles over the continental shelf, forming a cold and saline water mass of DSW (Ohshima et al., 2007). DSW uptakes various gasses, such as CO2, O2, and CFC, from the atmosphere when this water is formed. Further DSW is important for the transport of material and the biogeochemical cycle in the Pan Okhotsk region, as discussed in the next section (Yamamoto-Kawai et al., 2004).

This water flows out from the shelf due to buoyancy in the intermediate layer (around 400m in depth) along the eastern coast of Sakhalin Island. This water is often called the Okhotsk Sea Intermediate Water (OSIW). After experiencing strong tidal mixing along the Kuril Islands, the water originating in DSW outflows to the North Pacific Ocean and forms NPIW at a depth of 200m to 800m. DSW is a driving force behind the circulation in the intermediate layer of the Okhotsk Sea and the Pacific Ocean.

Recently, it was determined that there is a warming trend in OSIW and NPIW. This trend is the most evident in OSIW along the east coast of Sakhalin (47.5–50N, 145–147.5E), where 0.68℃/50 is observed (Nakanowatari et al., 2007), and is one of the largest warming trends in the world ocean, extending to the western North Pacific. Since the western Okhotsk Sea is a pathway of DSW, it is likely that the decrease in DSW production leads to the warming of the intermediate layer in this area.

It has also been determined that dissolved oxygen decreases in the Sea of Okhotsk and the North Pacific. The linear trend in the Sea of Okhotsk has been –0.58±0.34ml/l for the past 45 years. The value of the North Pacific is lower than that of the Sea of Okhotsk, although the decrease is still significant. Since dissolved oxygen may be considered as an index of the intensity of the overturning circulation, the decrease in the oxygen concentration suggests that the intermediate circulation may be weakening.

These facts suggest that the rate of dense water formation may have been on the decrease in recent years because the cold water property of OSIW is retained by mixing with DSW from the northern shelf. Although reliable estimates of the DSW formation rate are not available yet, there is indirect evidence of its decrease. Since the DSW formation is directly linked to sea ice formation in the northwestern shelf, we may examine the variation of the sea ice extent measured by satellite. Indeed, the sea ice extent has shown a decreasing tendency of 9.7% for the last 27 years. This indicates that the volume of DSW production should have decreased in the past years. Moreover, there is a significant correlation between the air temperature immediately upwind in Siberia and the sea ice extent in the Sea of Okhotsk, and, therefore, the decrease in the sea ice extent is probably a consequence of global warming.

MATERIAL CIRCULATION IN THE PAN-OKHOTSK REGION

DSW and OSIW were observed to carry a large amount of materials from the northwestern shelf of the Sea of Okhotsk. This fact was shown directly as high turbidity and high CFC concentration in DSW and OSIW. The decrease in the DSW formation is therefore likely to cause a reduction in the transport of materials as well. Among other types of material circulation, we are particularly interested in the circulation of iron. Iron is an essential nutrient for phytoplankton growth. Since iron does not easily dissolve in the ocean, it tends to be the first nutrient to lack, and, hence, it is one of the nutrients controlling the phytoplankton bloom in the upper ocean of WSP (Tsuda et al., 2003).

Iron originates in land surface. Previously, atmospheric dust was thought to be the most important source of iron and support the annual biological production in WSP. This is *the airborne iron hypothesis*, which supports the view that, in spring, iron in an aerosol form may fly together with yellow dust from Central Asia and precipitate over the Sea of Okhotsk and WSP. However, the connection between the dust input and biological production is not yet clear. Indeed, we have seldom observed sequential evidence of dust supply and phytoplankton bloom in WSP. Furthermore, the yellow dust precipitation varies greatly year by year, but spring time phytoplankton bloom occurs regularly in WSP.

Here, we propose that there is another source of iron to the WSP, which is related to the intermediate circulation, as suggested above (Nishioka et al., 2007). We call this *the intermediate- water iron hypothesis*. Iron does not dissolve easily in the ocean; thus, it is removed from there due to chemical processes and accumulated in the shelf sediment. Nevertheless, some of the iron particulates are resuspended and transported in dissolved forms. We thus hypothesize that iron is taken up first into

DSW by strong tidal mixing over the shallow shelf and then transported by OSIW out to WSP. In fact, we found extremely high concentrations of dissolved and particulate iron in OSIW, indicating that DSW uptakes it from the northwestern shelf region of the Sea of Okhotsk.

If iron in OSIW is transported only through the intermediate layer, however, it cannot be used by phytoplankton because the intermediate layer is too deep and sunlight cannot reach it, which is needed for photosynthesis. Therefore, the intermediate-layer iron should surface somewhere. The observation near the Kuril Islands conducted last year clarified this question. It is well-known that tidal mixing is particularly strong along the islands. Last year's observation showed that iron is distributed uniformly through the water column due to tidal mixing. This indicates that the intermediate-layer iron surfaces there and that, as a result, the upper ocean iron concentration there is higher than it is in other areas.

Furthermore, our time-series data in the Oyashio region indicates that the pattern of seasonal change in the dissolved iron concentrations in the surface layer is similar to that of other nutrients and that deep vertical water mixing resulted in higher winter concentrations of iron in the surface water of this region. The estimated iron supply from the iron-rich intermediate waters to the surface waters in the Oyashio region and the WSP was comparable to or higher than the reported atmospheric dust iron input and, thus, a major source of iron in these regions. In addition, a longitudinal section of the iron profiles in the North Pacific along 165º E clearly indicates that this source of iron is transported to a wide area of the WSP via the intermediate water layer.

In conclusion, our data indicates that iron is transported from the northwestern shelf region of the Sea of Okhotsk to a wide area of the western North Pacific via the intermediate water layer and that this source of iron is likely to support spring biological production in the WSP. The consideration of this source of iron is essential in our understanding of the biogeochemical iron cycles in WSP and the role of the marginal sea.

LAND SURFACE PROCESSES

The northwestern shelf of the Sea of Okhotsk, where ice formation occurs, is located just downstream of the mouth of the Amur River.

Since iron originates from the land, we hypothesize that iron observed in the intermediate layer (at least part of it) comes from the Amur River basin through riverine processes.

In order for iron to be dissolved in the river water, iron should form an iron-humate complex. Recent observations showed that wetlands are a major source of iron. The Amur River basin is a particularly flat basin; thus, a vast area of wetlands develops there. It was shown that the maximum iron concentrations occur in March and July in the middle and lower Amur River, when the water flux increases due to snow-melting water and large precipitation during the rainy season. Adjacent small rivers that flow through the wetlands contain particularly high iron concentrations and show similar concentration variations to those of the Amur River. Therefore, wetlands are important for maintaining both a high iron concentration and variation in the Amur River. Further investigation is underway by collecting seasonal water sampling at monitoring stations along the Amur River as well as by research cruises (Nagao et al., 2007).

The Amur River basin tends to be dry due to global warming. This suggests that the Amur River discharge may decrease in association with global warming and that the area of the wetlands may decrease. Both of these events can have significant impacts on the iron source to the Sea of Okhotsk.

Furthermore, land use change by human activity, e.g., the alteration of wetlands to plantations, may also influence the flux of dissolved iron. In the Sanjian Plain, for example, the concentrations of dissolved iron in the interstitial water in the soil horizons were measured repeatedly from May to November 2006. The highest concentration was always found in water from natural wetlands, whereas the lowest one was from cultivated dry land (Shibata et al., 2007). Paddy fields showed intermediate concentrations. The concentration of dissolved iron was also found to be dependent upon the water table even in the same land-use type. Since a land use and vegetation map of Amur River basin has been compiled using satellite images from the Land Sat 7 with a resolution of 50–100m, we may be able to estimate the variation of the iron flux as well as the water flux data of the Amur River.

SUMMARY AND CONCLUDING REMARKS

Warming in the intermediate layer of the Sea of Okhotsk is a very clear signature of global warming adjacent to Japan. The trend of the temperature increase is 0.68℃ in 50 years, which is one of the largest warming trends in the world ocean. Therefore, it is very important to understand how it occurs and how it influences the Pan-Okhotsk environment. The following sequences are likely to be linkages between global warming and the intermediate layer warming:

Warming over northeastern Eurasian Continent in fall and winter due to **global warming.**

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Warming and/or weakening of the winter monsoon over the Sea of Okhotsk.

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Decrease in sea ice production in the northwestern shelf of the Sea of Okhotsk.

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Decrease in dense shelf water (DSW) formation because of a reduction of brine rejection from sea ice.

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Weakening of intermediate-layer overturning in the Sea of Okhotsk and the western subarctic Pacific associated with DSW weakening.

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Decrease of the cold DSW input to the intermediate layer, causing **warming of the intermediate layer**.

It is also hypothesized that the weakening of the intermediate-layer overturning may reduce the transport of materials. Among other types of material circulation, we have paid attention to the circulation of iron, as iron is an essential nutrient for phytoplankton to grow. It has been shown from observations that there is a high concentration of iron in the intermediate layer of the Sea of Okhotsk and the western subarctic Pacific, which may be utilized by phytoplankton after iron surfaces due to tidal mixing along the Kuril Islands and winter-time deep convection. The weakening of intermediate-layer overturning is therefore likely to cause a reduction in the iron transport. Indeed, in the Oyashio region, phytoplankton production has decreased for the last 30 years. We have not yet identified the cause of this decrease yet, but the reduction of iron transport may explain it.

Since iron originates from the land, the Amur River may be a source of iron to the northwestern shelf of the Sea of Okhotsk. This implies that not only the intermediate-layer circulation but also the iron flux from the river may be influenced by global warming. The iron flux may also be affected by human activity by changing land use and vegetation in the Amur River basin. Since the Amur-Okhotsk system spans three countries, i.e., Russia, China, and Japan, it is not easy to negotiate environmental issues in this region. Nevertheless, scientific data should provide the basis for discussion of the Pan-Okhotsk environmental problems. The Pan-Okhotsk Research Center is expected to clarify scientific issues related to the environmental problems in this region.

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