RECENT STUDIES OF THE SEA OF OKHOTSK

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ABSTRACT

We recently have had a Japan-Russia-United States International Joint Project, 1997-2002. In this project, we have carried out intensive oceanographic observations in the almost entire Sea of Okhotsk for the first time, using a Russian research vessel; we have had four times cruises, changing seasons. This report summarizes several new findings for the Sea of Okhotsk which were obtained by this project, for examples, the major location of the sea ice production and its growth history, the structure and seasonal variability of the East Sakhalin Current and its formation mechanism, and the systems of water circulation and material cycle which make this sea to be the area of high biological productivity. Finally, we have found out the warming and oxygen-decreasing trends of intermediate water in the northwestern North Pacific during the past 50 years, originating from the Sea of Okhotsk. This result suggests that the overturning in the Sea of Okhotsk and the North Pacific will be weakened and the resulting go-down of biological productivity is concerned.

KEY WORDS; Sea of Okhotsk, Sea ice, East Sakhalin Current, System of material cycle, Coastal polynya

INTRODUCTION

Although the Sea of Okhotsk is a small and marginal sea, it is surrounded with the geographically unique environment. The Sea has the largest continent and the largest ocean in the world, to the west and east, respectively, and also has meridionally large surface-air temperature gradient, with the Arctic region and the subtropical region to the north and south, respectively. The characteristic environment causes this region to have a seasonal reversal in the zonal and meridional surface-air temperature gradients.

Because the coldest region in the Northern Hemisphere exists in the East Siberia region just north of the Sea of Okhotsk, the cold air masses are transported toward the Sea by cold, strong northwesterly wind in winter; hence, it is widely believed that the Sea of Okhotsk is one of the southernmost seasonal sea ice zone in the Northern Hemisphere. And, it is recently noticed that the Sea of Okhotsk also is the important locations for the ventilation of the North Pacific Intermediate Water, the absorption of carbon dioxide and the high biological productivity. In spite of such geophysical and earth environmental significances, however, we have had very few oceanographic and sea-ice observations in the Sea of Okhotsk.

The major purpose of this paper is to present several new findings for the Sea of Okhotsk which were revealed by the Japan-Russia-United States international joint project on the Sea during 1997-2002.
1. SEA ICE

We first examine the locations of sea-ice formation in the Sea of Okhotsk, using two different kinds of analytical methods, SSM/I microwave data analysis (Kimura and Wakatsuchi, 2004) and heat-budget calculations (Ohshima et al., 2003). Both these analyses show that the major location of sea ice formation is an open water area, so called a coastal polynya, off the East Siberian coast, as shown in Figure 1. In the coastal polynya, the continuous blowing of cold, strong northwesterly wind will maintain the open-water area or thin-ice area throughout the winter. As the result, the large amounts of net sea ice formation will occur efficiently. According to our data analyses (Ohshima et al., 2003), almost all the sea ice entirely covering with the Sea of Okhotsk forms in the coastal polynya of the northwestern shelf and widely extends eastward and southward by wind and ocean current.

We also have done the structural analyses of sea-ice samples collected in the southern part of the Sea off the Hokkaido coast. These analyses show that most of the thick ice is composed of several ice plates with different ice growth histories (Toyota et al., 2004); hence, it is supposed that almost all the thick ice does not form in the coastal polynya directly but dynamically grows through the rafting processes during the southward drifting.
2. WATER CIRCULATION

We have had completely no information of water-circulation system in the Sea of Okhotsk as well as the East Sakhalin Current. In this project, therefore, we have investigated significant, oceanographic topics to be solved for the Sea, for examples, the structure and seasonal variability of the East Sakhalin Current, water exchange between the Sea of Okhotsk and the North Pacific, the system of material cycle and air-sea interaction etc. For this investigation, we have carried out intensive oceanographic observations in the almost entire Sea of Okhotsk with four times cruises aboard a Russian research vessel, Prof. Khromov during 1998-2001.

Figure 2 shows a schematic drawing of the sub-surface water circulation in the Sea of Okhotsk which was derived on the basis of observational data with the deployment of 20 Argos buoy floats during a half year from September, 1999 through February 2000 (Ohshima et al., 2002). This figure also shows that the East Sakhalin Current has two cores; one core flows southward along the East Sakhalin coastal line toward the Hokkaido coast, while another core flows offshore and southward, turning eastward at a latitude of 47.5°N. A considerable amount of the Okhotsk Sea water ultimately outflows to the North Pacific through the Bussol' Strait, having several anticyclonic mesoscale eddies with a dimension of 100 km or 200 km in diameter, in the deep Kuril Basin.

![Diagram of water circulation](image)

*Figure 2: Schematic illustration of near-surface water circulation for the Sea of Okhotsk which was derived from satellite-tracked drifter data. (Ohshima et al., 2002) Thicker arrows represent the stronger flow. Currents in the eastern part are depicted by dotted lines because they are based on speculation.*
We next observed the structure and seasonal variability of the East Sakhalin Current. As shown in Figure 3, the East Sakhalin Current has a horizontal width of about 150 km and the maximum depth of about 1500 m, being characterized by the large seasonal variability for the volume transport (Mizuta et al., 2003). According to a theoretical study (Ohshima et al., 2004), the East Sakhalin Current can be explained as a wind-driven western boundary current; hence, this current has the maximum transport ($12.5 \times 10^6$ m$^3$/s, or about 12.5 Sv) at 53°N on February when there is a strong wind system and the minimum one (about 1 Sv) on October when there is a weak wind system.

We also have carried out intensive oceanographic observations of water exchange between the Sea of Okhotsk and the North Pacific (Katsumata et al., 2004). Our observational results and data analysis show that the major water exchange between the above two basin is made through the Bussol’ Strait and Kruzenshtern Strait. In the north-side strait, Kruzenshtern Strait, the warm, saline and oxygen-poor Pacific water inflows and meets with the circulation in the Sea of Okhotsk, its properties being modified, and ultimately, the cold, fresh and oxygen-rich water outflows to the North Pacific through the south-side strait, Bussol’ Strait (net outflow of about 9 Sv).

Figure 3: (a) Contours of the annual-mean transport (Sv), which is integrated from the surface at the coast to a given point, along a vertical cross section at 53°N. Contour interval is 0.5 or 1 Sv. Areas 1 and 2 are regions of the surface-trapped flow associated with the East Sakhalin Current Water (ESCW), and the bottom-intensified flow associated with the Dense Shelf Water (DSW), respectively. Dots represent positions at which velocity data were obtained. (b) Time series of the monthly mean transport (Sv) for ESCW at 53°N. (Mizuta et al., 2003)

3. SYSTEM OF MATERIAL CYCLE

We next examine the system of material cycle in and around the Sea of Okhotsk. It is well known that both the northern North Pacific and the Sea of Okhotsk are one of the
highest-biological productivity areas in the world. The spatial distribution of nutrients in the Northern Hemisphere shows that in the northwestern North Pacific, large amounts of nutrients still remain even in summer when the active blooming of phytoplankton occurs while in the Sea of Okhotsk, almost all the nutrients are disappeared from the sea. According to recent study (Martin and Fitzwater, 1988), this phenomenon in which the excess nutrients exist in the northwestern North Pacific even in summer may be highly caused by iron deficiency in seawater.

Figure 4 shows the spatial distribution of total dissolvable iron within seawater around the Kuril Islands which was derived by observational data (Nishioka, 2004). This figure shows that the amount of iron approximately increases toward the Sea of Okhotsk zonally; hence, the iron origin may exist in the Sea of Okhotsk and/or the Eurasian continent. Unfortunately, we did not carry out iron observations in our project. However, we have done the organic carbon observations within the Sea of Okhotsk, by water samplings (Nakatsuka et al., 2002; 2004a; 2004b). According to these observations, considerable amounts of the organic carbons are successfully trapped by cold, dense-shelf water produced with the active sea ice formation in the coastal polynya, and are widely transported into the intermediate layer of the Sea of Okhotsk.

Figure 4: (a) Spatial distribution of total dissolvable iron around the Kuril Islands which was derived on the basis of observational data for (b) iron vertical profiles; dots are data from the Sea of Okhotsk, triangles from the Oyashio region, and crosses from the western subarctic Pacific. (Nishioka, 2004)

From all the above observational data, we can imagine the existence of nice systems of water circulation and material cycle which are characteristic of the Sea of Okhotsk as the follows. Almost all the sea ice entirely covering with the Sea of Okhotsk forms in the northwestern coastal polynya off the East Siberia coast. The large amounts of sea ice formation in the coastal polynya simultaneously causes very much brine rejection into the underlying seawater and produces dense-shelf water (Shcherbina et al., 2003). The dense-shelf water flows southward together with the East Sakhalin Current, including the nutrients, probably from the Amur River (Nakatsuka et al., 2004a), and eventually may outflow to the western North Pacific through the central Sea of Okhotsk (Katsumata et al., 2004; Yamamoto, et al., 2004).
4. EFFECT OF GLOBAL WARMING

It is widely believed that the global warming is recently proceeding and the East Siberia region just north of the Sea of Okhotsk is one of the most sensitive areas to the global warming in the Northern Hemisphere. Figure 5 shows the linear trend map of the intermediate water temperature on $27.0\sigma_\theta$ in the Sea of Okhotsk and the North Pacific during the past 50 years, 1955-2004 (Nakanowatari et al., 2006). This figure clearly shows that the largest warming area exists in the western part of the Sea of Okhotsk, and the warming trend widely extends toward the western North Pacific. Therefore, the origin of this warming may come from the northwestern Sea of Okhotsk and/or the Eurasian continent.

![Figure 5: Linear trend of water temperature anomalies in °C/50-year at density of 27.0σθ from 1955-2004 in the northwestern North Pacific. Large and small dots indicate the grid boxes at which the linear trend is significant at the 99% and 95% confidence level, respectively. White color area indicates the grid boxes where yearly temperature anomalies are not available for more than 10 years throughout the respective periods for the linear trend calculation. The significance of the linear trend estimate is based on a Student t distribution. (Nakanowatari et al., 2006)](image)

On the other hand, there is a decreasing trend of the Okhotsk sea ice extent during the past 20 years, 1980-2000. From all the observational results, we can derive a hypothesis as follows; the global warming causes the decreases of both the sea-ice formation and the dense-shelf water production. As the result, the intermediate water circulation will be weakened, and the go-down of biological productivity will occur probably.

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