CIRCULATION AND HEAT/SALT TRANSPORT IN THE SEA OF OKHOTSK AND ITS RELATION TO SEA ICE

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INTRODUCTION

The Sea of Okhotsk is the southernmost seasonal ice zone in the Northern Hemisphere with large interannual variations of sea ice extent, and thus it can be considered as a sensitive indicator of climate change. North Pacific Intermediate Water (NPIW) is ventilated mainly in and around the Okhotsk Sea (Talley, 1991). In other words, the Okhotsk Sea can be regarded as the only site that the atmosphere can directly exchange the heat and material (including CO2) with the intermediate water in the North Pacific. Thus, water-mass formation has been studied in several papers (e.g., Kitani, 1973).

However, the circulation of this sea had not yet been well understood due to the lack of direct current measurements. The Okhotsk circulation was presented only schematically, based on water-mass distribution, ship and ice drift, and sporadic short-term current measurement (Moroshkin, 1966; Luchin, 1998). According to their schematic figures, a cyclonic gyre dominates the northern half of the Okhotsk with a southward boundary current along Sakhalin Island, historically called the East Sakhalin Current (hereafter ESC).

The Joint Japanese-Russian-U.S. Study of the Sea of Okhotsk, carried out during 1998-2001, has considerably revealed the oceanography of the Okhotsk Sea : its circulation, water exchange with North Pacific, dense shelf water formation, heat/salt budget, the role of sea ice etc. In this paper, these results are summarized, together with heat flux calculation.

1. CIRCULATION IN THE SEA OF OKHOTSK

Under the Joint project, intensive direct current observations have been made during 1998-2001 in this sea both from Lagrangian and Eulerian measurements. Figure 1 shows the spatial distribution of the mean surface flow derived from 20 surface drifters (Ohshima et al., 2002). The figure clearly shows that the southward East Sakhalin Current is a steady feature with typical speeds of 0.2-0.3 m s^{-1} (the mean velocities exceed the error ellipses significantly). This figure also shows that a part of this southward current continues as far as the southern tip of Sakhalin Island while a part of the current turns to the east around Terpeniya Bay (48°N) flowing eastward as far as Bussol' Strait. This eastward current together with the southward East Sakhalin Current constitutes a part of the cyclonic gyre in the Okhotsk Sea. The fact that all the drifters in the western part move southward implies the compensated northward flow in the eastern part of the Okhotsk Sea.

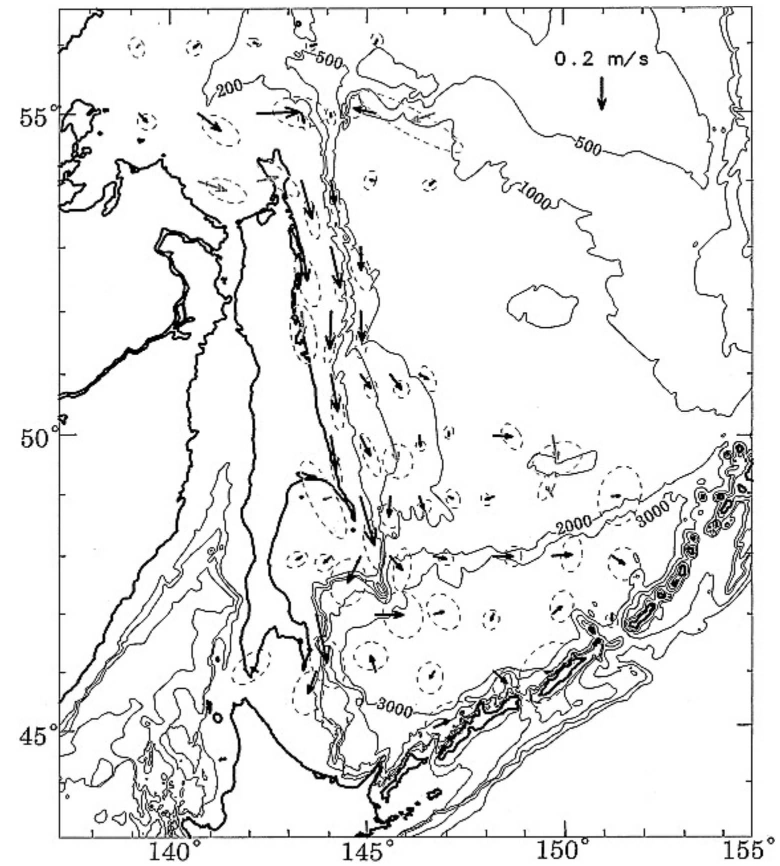

Figure 1: Mean velocity vectors for 1.5°longitude × 1°latitude bin derived from 20 surface drifters. The results for bins with less than 3 drifter-days are not shown and those with less than 10 drifter-days are indicated by gray arrows. The 95 percent confidence error ellipses are also drawn around the tip of the vectors. (Ohshima et al., 2002)

Figure 2 shows the mean velocity vectors as a function of depth range for 51.5-55°N in the ESC region. The ESC appears to consist of two cores: one exists near the coast (50-150 m depths) with typical speeds of 0.3-0.4 m s^{-1} and the other over the shelf slope (300-900 m depths) with typical speeds of 0.2-0.3 m s^{-1}. In the upstream of the currents the nearshore core appears to originate from the northwest shelf while the shelf slope core from the east (Figure 1). On the other hand in the downstream, the nearshore core may be relevant to the southward branch extending toward the southern tip of the Sakhalin Island while the slope core to the eastward branch turning to the east and flowing eastward as far as Bussol' Strait.

Most of the drifters that survived in the Okhotsk Sea went out to the Pacific through Bussol' Strait in less than a half year, suggesting that Bussol' Strait is the main pathway for the surface water to flow out from the Okhotsk Sea and that the surface water in the Kuril Basin and the east Sakhalin shelf has relatively short resident time of less than 1 year. Mesoscale eddy features, mostly anticyclonic eddies, are dominant in the Kuril Basin (Ohshima et al., 2005).

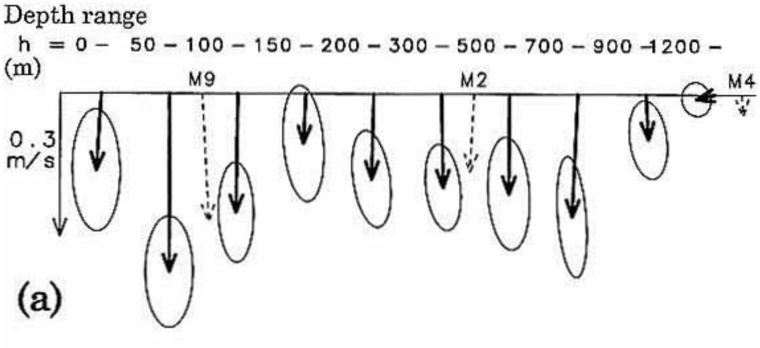

Figure 2. Mean velocity vectors as a function of bottom depth range with a coordinate aligned with the depth contour direction for 51.5-55°N in the East Sakhalin Current region. The associated 95 percent confidence error ellipses are also shown at the tip of the vectors. Mean velocity vectors from the moorings are also shown by dashed lines. (Ohshima et al., 2002)

Figure 3 is a schematic of the circulation and mesoscale features of the Okhotsk Sea derived from the surface drifter data. Observed circulation is basically compatible with the schematics of Moroshkin (1966).

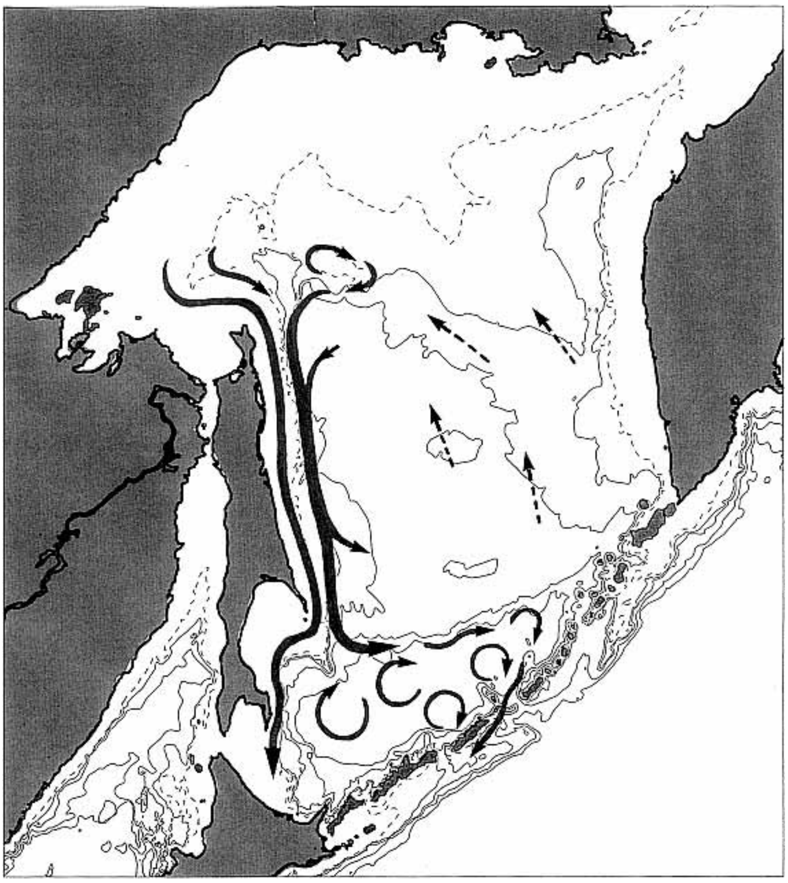

Figure 3: Schematic of near-surface circulation for the Sea of Okhotsk as derived from our satellite-tracked drifter data. Thicker arrows represent the stronger flow. Currents in the eastern part are depicted by dotted lines because they are based on speculation.

Geopotential anomaly at 100 dbar relative to 1000 dbar (Figure 4) also clearly suggests the cyclonic gyre in the Central Basin (Ohshima et al., 2004). The overall pattern is consistent with the circulation obtained from surface drifters. Figure 4 also indicates an anticyclonic circulation in the Kuril Basin. This circulation has already been described in Wakatsuchi and Martin (1991). So far 20 profiling floats have been deployed in the Okhotsk Sea. From the trajectories of these floats drifting at depths of 500 m and 750 m, the cyclonic gyre is found to extend to the intermediate depths.

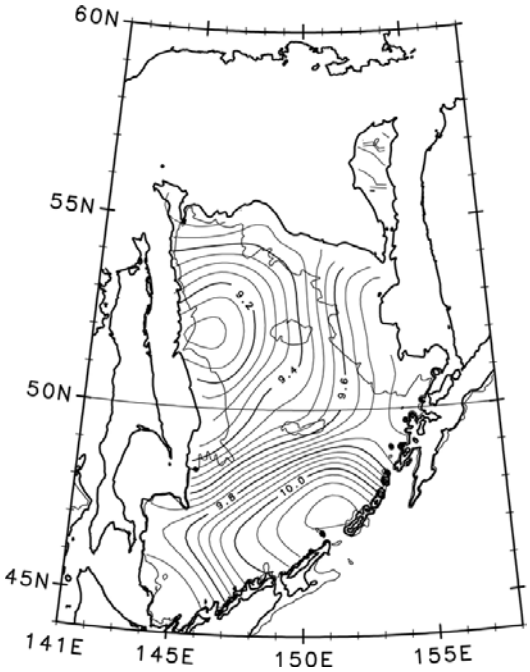

Figure 4: A chart of geopotential anomaly of 100-dbar surface relative to 1000-dbar surface in dynamic meter×10. The contour interval is 0.05 in dynamic meter×10. For the value of geopotential anomaly in the area shallower than the reference level of 1000 dbar, the extrapolation is made. (Ohshima et al., 2004)

Figure 5 shows a vertical cross section of monthly mean meridional velocity of the ESC in January 1999, based on the mooring array of current meters at 53°N (Mizuta et al., 2003). In January the southward flow speed attained a maximum over the shelf-slope, and the flow extends to the bottom on the slope. In other seasons, the flow also extends to the bottom, although its speed exhibits the large seasonal variations. Figure 6 shows the seasonal variation of the ESC transport observed by the mooring array at 53°N (Mizuta et al., 2003). The ESC transport exhibits large seasonal variations, with a maximum of 12.3 Sv in February and minimum in summer. The annual average volume transport of the ESC is estimated to be 6.7 Sv, which is three times as large as that of the Tsushima Warm Current. The mooring array showed that a major part of the ESC transport exists in the shelf-slope core.

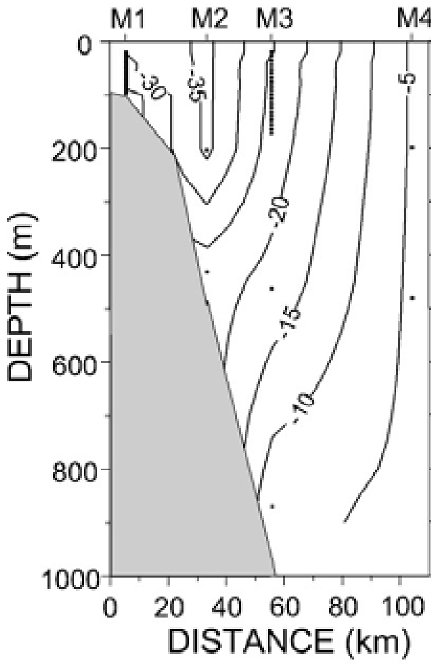

Figure 5: Monthly mean velocity component (cm s^{-1}) normal to a vertical cross section at 53°N in January 1999. Positive value indicates a southward flow. (Mizuta et al., 2003)

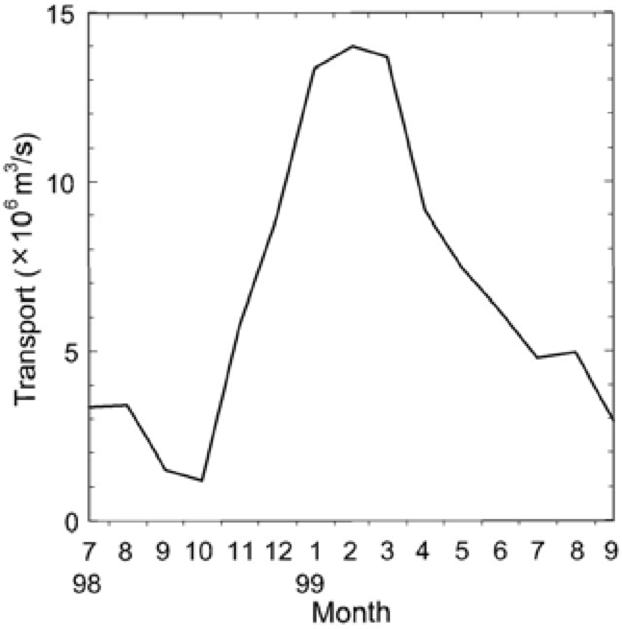

Figure 6: Seasonal variation of the ESC transport observed by moorings at 53°N. Southward transport is taken positive. (Mizuta et al., 2003)

2. Exchange of water, heat, and salinity with the North Pacific

Intensive LADCP and CTD observations have been carried out across the Bussol' Strait, the largest strait in the Kuril Islands. Figure 7 shows the mean components of the long-channel flow at the spring tide across the Bussol' Strait (Katsumata et al., 2004). The observations revealed a two-layer structure of the mean flow across the strait, where the upper layer flows out of the Okhotsk and the lower layer in the opposite direction. By integrating in the cross section, the transport through the strait is 9 Sv outflow from the Okhotsk. It is also demonstrated that the tidal amplitude reaches more than 1 m s^{-1} even in the depth greater than 1000m, suggesting the strong tidal mixing around the Kuril Straits.

Based on the LADCP and CTD observations, net heat and salt exchange between the Okhotsk Sea and the North Pacific are estimated; net heat flux of -34 terawatts and net salt flux of -1.9 $\times 10^6$ kg s^{-1} are exchanged from the Okhotsk Sea to the North Pacific.

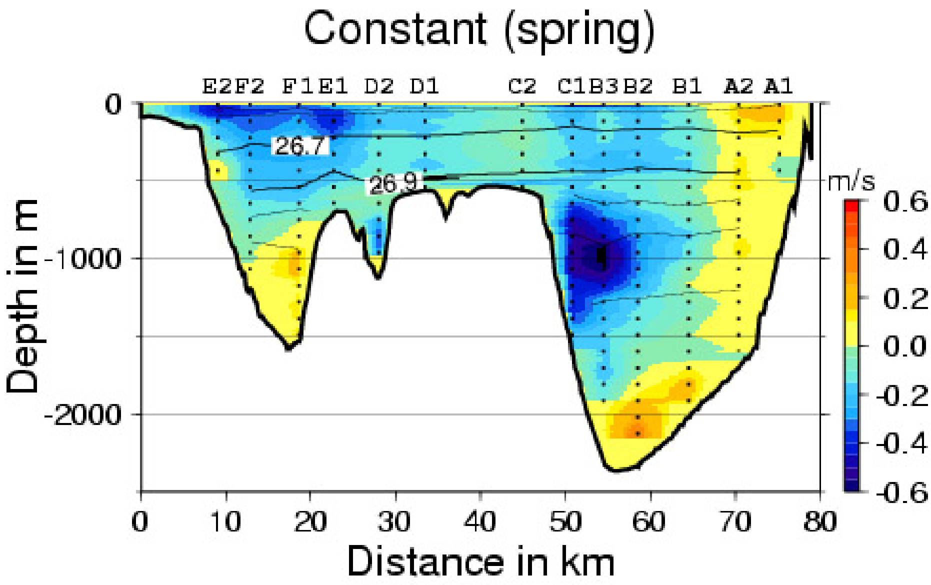

Figure 7: Mean components of the long-channel flow at the spring tide across the Bussol' Strait. The positive sign indicates the flow toward the Okhotsk, into the paper. (Katsumata et al., 2004)

3. Heat Budget/Transport and Its Relation to Sea Ice

To examine the heat budget and its transport in the Okhotsk Sea, the surface heat flux over the Sea of Okhotsk has been calculated from 1987 to 2001 by bulk parameterizations using ECMWF, ISCCP, and GISST data, corrected by COADS data. Sea ice concentration and ice type are incorporated by using an SSM/I open water and thin-ice algorithm to better represent the sea ice conditions. Figure 8 shows the geographic distribution of annual net heat flux (Ohshima et al., 2003). Figure illustrates a distinct contrast, significant cooling of the ocean in the north, and net heating of the ocean in the south. This contrast is a result of negative heat transport by both sea ice and the southward East Sakhalin Current. In the north, sea ice, through its formation, releases latent heat, resulting in large heat transport to the atmosphere in winter. While in the south, sea ice, through melting, absorbs latent heat from the ocean, resulting in relatively large heat flux from the atmosphere from spring to summer. Through sea ice, heat is transported from the southern ocean to the northern atmosphere. A part of the East Sakhalin Current originates from the northwest shelf and extends as far as offshore of Hokkaido, which can transport a large amount of cold water from the north. These negative heat transports by both sea ice and the current are possible factors causing the cold summer climate of eastern Hokkaido.

Using a heat budget calculation, we try to estimate sea ice production. Oceanic heat flux from below is assumed to be negligible. Then the amount of ice production corresponds to negative value of net heat budget in ice and polynya area. Figure 9 shows the spatial distribution of annual cumulative ice production averaged over 1987-2001. It is found that most of the ice production in the Okhotsk Sea is accomplished in the coastal polynyas. Particularly, the northwest shelf is by far the highest ice production area in the Okhotsk Sea. This is consistent with the fact that most of Dense Shelf Water is produced in this area.

The present calculation results in a negative net heat budget of -22 W m^{-2} and the total heat loss of 35 terawatts for the entire Okhotsk Sea; the sea loses heat to the air. This value approximately coincides with the flux calculation in the straits described in the previous section. This is consistent with the general understanding of the in- and outflow system of the Okhotsk Sea; Soya Warm Current Water from the Japan Sea and relatively warmer water from the Pacific flow into the Okhotsk Sea, and colder water flows out to the Pacific (Talley, 1991). A part of the net heat loss in the Okhotsk contributes to the following heat flow; cold Dense Shelf Water produced in the polynyas constitutes a part of the Okhotsk Sea Intermediate Water, which finally flows out to the Pacific with negative heat. By assuming that the heat flux across the ocean-land boundary is insignificant, the Okhotsk Sea is an area where heat is transported northward, by contrast to the same latitudinal area in the North Pacific (Moisan and Niiler, 1998).

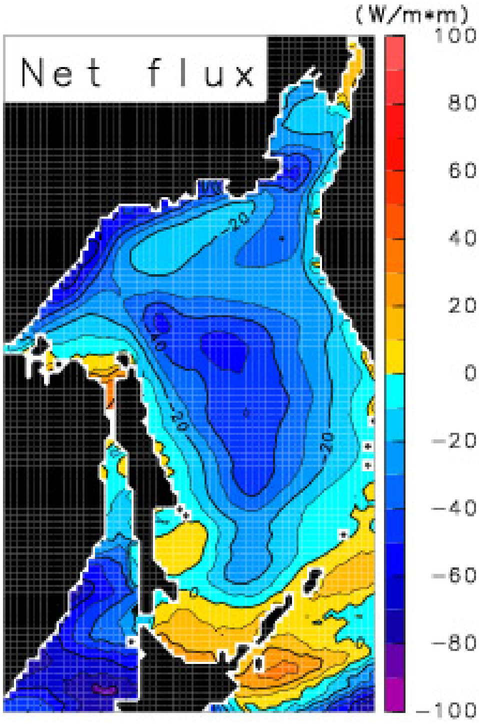

Figure 8: Annual mean net heat flux during 1987-2001. A positive value indicates that the sea (or sea ice) gains heat from the air. Areas with negative values are dotted. The contour interval is 10 W m^{-2}. (Ohshima et al., 2003)

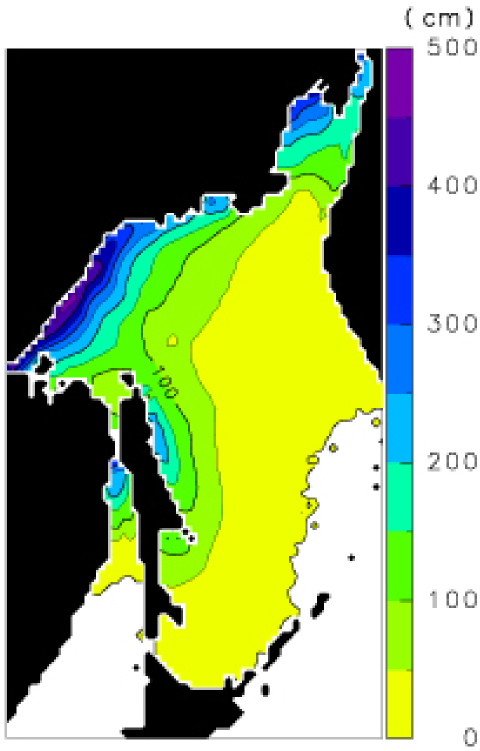

Figure 9: Spatial distribution of annual cumulative ice production (represented by the ice thickness: cm) averaged over 1987-2001. (Ohshima et al., 2003)

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