Tracing dense shelf water in the Sea of Okhotsk with an ocean general circulation model

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Abstract:
A lot of sedimentary particles are known to be mixed into dense shelf water (DSW) produced in the northern part of the Sea of Okhotsk as a result of brine rejection during sea ice formation. To investigate the behavior and distribution of materials in DSW, tracer experiments with an ice-ocean coupled model have been conducted. It was shown that a tracer injected in winter over the northwestern shelf flows on the shelf until early summer with the concentration higher near the bottom. Then, it goes down along the slope to the intermediate layer along the east coast of Sakhalin; the core of tracer is settled around a depth of 400 m. These features are consistent with observations. The experiment in which tidal mixing is absent along the Kuril Islands shows a shallower core of the tracer at a depth of about 200 m owing to the density decrease of DSW.

KEYWORDS dense shelf water; the Sea of Okhotsk; tracer; intermediate layer; tidal mixing; numerical experiment

INTRODUCTION

A large amount of sea ice production occurs in the northwestern shelf (Figure 1) of the Sea of Okhotsk (e.g. Nishashi et al., 2009). Associated with the ice formation, cold and saline dense shelf water (DSW) is formed there in winter as extremely saline water, called brine, is rejected from sea ice (Kitani, 1973; Shcherbina et al., 2003). Then, DSW outflows from the shelf, and moves southward along Sakhalin to the Kuril Basin, mixing with surrounding water (Yamamoto et al., 2002; Fukumachi et al., 2004; Yamamoto-Kawai et al., 2004). In the Kuril Basin, it mixes further with other waters originating from the Japan Sea and the Pacific. The mixed water flows out from the Sea of Okhotsk and finally extends to the Pacific in its intermediate layer (e.g. Talley, 1991; Watanabe and Wakatsuchi, 1998).

The northwestern shelf is located near the mouth of the Amur River. Various materials contained in the river water pour into the northwestern shelf and accumulate there. Based on observations, Nakatsuka et al. (2002, 2004) suggested the following hypothesis: DSW creeps on the shelf during spring and summer incorporating sedimentary particles, and then it flows southward in the intermediate layer along Sakhalin in autumn and finally flows into the Pacific. Thus, many materials are considered to be supplied to the Pacific through the intermediate layer circulation. Among those materials, iron has especially been attracted because it is a critical factor to the biological production in the western subarctic Pacific (Nishioka et al., 2007). Therefore, to simulate transport of those materials is important for biogeochemical processes in the Pacific as well as in the Sea of Okhotsk.

In the present study, we conduct a numerical experiment where a tracer is injected in the northwestern shelf in winter. The aim is to trace DSW, as well as to observe behavior of materials included in DSW. We focus particularly on its transport processes in the northwestern shelf and the slope near the northwestern shelf. We intend this simulation to be a step for improving biogeochemical modelings in and around the Okhotsk Sea. Additionally, it is interesting to investigate behavior of DSW produced under a low sea surface salinity (SSS) condition because the depth of the path of DSW depends on the density of DSW, which depends on SSS. Here, we also conduct an experiment without the tidal mixing effects as an example of a low SSS condition, although wind stress and the Amur River discharge also bring about change in SSS as shown by Matusda et al. (2009).

EXPERIMENTAL DESIGN

The ice-ocean coupled model used in the present study is based on CCSR Ocean Component Model, version 3.4 (Hasumi, 2006). As the model configurations are similar to that used by Matsuda et al. (2009), we here describe the bare necessities, including the differences from theirs.

The model domain spans from 136°E to 179.5°W and from 39° N to 63.5° N (Figure 1). The horizontal grid spacing is 0.5° and there are 51 vertical levels with a resolution ranging from 1 m at the top level to 1000 m at the deepest level. The isopycnal and thickness diffusion coefficients (Cox, 1987; Gent et al., 1995) are 1.0 × 10⁵ and 3.0 × 10⁴ cm²/s, respectively. The model is forced at the sea surface by daily climatological atmospheric data in the Ocean Model Intercomparison Project dataset (Röskie, 2001). Potential temperature and salinity are restored to the monthly climatology (WOA; Conkright et al., 2002) on the open boundaries, as well as at grid points deeper than 2000 m. SSS is also restored to the WOA, except in the northern half of the Sea of Okhotsk in winter. The surface elevation is restored to the output of a basin-wide model on the boundaries.

Since this model does not directly simulate tides and associated mixing, we added a large vertical diffusivity coefficient along the Kuril Islands to represent tidal mixing.
effects. This additional mixing was set to be vertically constant in previous studies, which successfully reproduced DSW but had too much mixing near the surface along the Kuril Islands (Matsuda et al., 2009). To improve the latter deficiency with keeping the DSW reproduction, we used a vertically variable coefficient profile (Figure 1), based on the results that tidal mixing is the largest near the bottom (Nakamura and Awaji, 2004). We refer to the experiment as the standard case. We also conducted an experiment in which tidal mixing effects are not included (referred to as the no-tide case), as a low SSS case.

The model is integrated for 116 years as for spin-up. Then, we begin tracer experiments, where a passive tracer is restored to unity at the sea surface in the northwestern shelf (crosses in Figure 2 and the shaded region in Figure 3) from January to April, when brine rejection occurs owing to ice formation. Note that since the shelf is shallow, the tracer is mixed to the bottom during the DSW formation even though the tracer is restored at the surface.

RESULTS

First, we describe the standard case. The injected tracer moves southwestward along the coastline and then moves eastward around 55°N in the northwestern shelf on the 26.9 $\sigma_{\theta}$ surface (Figure 2a). After flowing out from the shelf, it is transported southward along Sakhalin, and extends over the Kuril Basin. This tracer distribution corresponds to current fields. On the northwestern shelf, water flows anticlockwise along the coast (Figure 3). The speed at (139°E, 55°N) is around 5.5 cm/s, which is comparable to an observed value, 6.3 cm/s, by Shcherbina et al. (2003). After the current bends to the south, there exists a strong southward current, called the East Sakhalin Current (ESC), along the east coast of Sakhalin (Ohshima et al., 2002). The relatively high concentration along Sakhalin indicates transport of the tracer by ESC. Further, some of the tracer extends northeastward around 52°N, owing to an anticlockwise recirculation gyre in the central part of the Okhotsk Sea. An observation with profiling floats by Ohshima et al. (2005) shows a signature of the recirculation gyre. This gyre can also be seen in a simulation with higher resolution models (e.g. Simizu and Ohshima, 2006). The concentration is rapidly decreasing as the tracer flows southward along Sakhalin, consistent with observational results (Yamamoto et al., 2002; Fukamachi et al., 2004). The ESC turns eastward around 47°N and therefore the tracer extends eastward along 47°N. Part of the ESC flows southward to Hokkaido in winter (Ohshima et al., 2002; Simizu and Ohshima, 2006; Uchimoto et al., 2007).
Figure 4 shows the monthly mean vertical distributions in the first year along the line denoted in Figure 2 (as well as in Figure 3). The tracer begins to appear in the western part of the shelf in February, when the density near the bottom of the shelf is lighter than $26.8 \sigma_\theta$. After that, the tracer moves eastward with the concentration higher near the bottom, and reaches the shelf break around June. At this time, the density reaches $27.0 \sigma_\theta$ near the bottom of the shelf. Then, the tracer goes down along the slope. In October, the core of the tracer on the slope lies around a depth of 400 m, whose density is between 26.9 and $27.0 \sigma_\theta$. Finally a large part of the tracer leaves the shelf around December (not shown).

Next, we describe the no-tide case (Figure 5). Until June, the tracer spreads at almost the same rate as that in the standard case. After that, when the tracer begins to subduct along the slope, the distribution becomes different from that in the standard case (October in Figures 4 and 5). The tracer in the no-tide case subducts to a shallower depth than in the standard case, where the core depth is about 200 m and density ranges between 26.8 and $26.9 \sigma_\theta$ respectively. Consequently, the core density differs by 0.1 $\sigma_\theta$ between the standard and the no-tide cases, although the horizontal tracer distributions are similar between the two cases over the core density surfaces (Figure 2). These differences are attributed to the fact that the density of DSW is different. Tidal mixing along the Kuril Islands makes DSW denser because salinity in the northwestern shelf increases indirectly owing to the tidal mixing, which induce upward salt flux along the Kuril Islands and the salty water is transported to the north (Nakamura et al., 2006; Matsuda et al., 2009).

DISCUSSION AND REMARKS

The tracer traces the core of DSW well. In Figure 4,
water denser than 26.9 \( \sigma_T \) and colder than \(-1^\circ C\) is indicated by cross-hatching, and is regarded as a DSW core. Although the tracer distributes in the wide range of density, water with highest concentration on the section corresponds to DSW. For example, water with tracer concentration higher than 0.85 in June and 0.45 in October almost corresponds to DSW. The same is true in the no-tide case (Figure 5), although DSW is defined in this case as the water denser than 26.8 \( \sigma_T \) and colder than \(-1^\circ C\). If we were using the same criteria for DSW in the no-tide case as that in the standard case, little DSW would be observed in the no-tide case. This is consistent with the experiments by Nakamura et al. (2006) and Matsuda et al. (2009).

The distributions of the tracer and DSW in Figure 4 are consistent with observations by Nakatsuka et al. (2002). They found that cold and extremely turbid water was present in September at a station close to location 15 in Figure 4. If we regard the tracer core as the turbid water, the water around 400 m depth at location 15 is shown to be highly turbid and very cold as was observed (the figure for September is not shown but similar to that for October in Figure 4). Further, DSW with abundant tracer begins to discharge to the slope in June, which is consistent with studies by Gladyshev et al. (2000). Therefore, the simulation represents the tracer transportation processes well.

In conclusion, the model successfully captures characteristics of tracer transport from the northwestern shelf of the Sea of Okhotsk with DSW produced when sea ice is formed. To our knowledge, this is the first simulation that can realistically represent transport of tracers with DSW in the Sea of Okhotsk. Based on this improved tracer simulation, improvement of biogeochemical simulation including intermediate-layer iron transport, found by Nishioka et al. (2007), is currently underway.

ACKNOWLEDGMENTS

We thank Dr. Nishioka for his comments. This study was supported by the New Energy and Industrial Technology Development Organization (NEDO). The figures were produced by GFD-DENNou Library.

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