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Long-term variation in sea ice production and its relation to the intermediate water in the Sea of Okhotsk

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ABSTRACT

Overturning in the North Pacific extending to the intermediate layer (about 200–800 m depth) originates from the sinking of dense shelf water (DSW) formed by sea ice production in the Okhotsk coastal polynyas. It has been suggested that this overturning has weakened during the past 50 years. The purpose of this study is to clarify the long-term variability of sea ice production in the polynyas and to discuss its linkage with DSW formation and the overturning. First, we have developed a thin ice thickness retrieval algorithm using Special Sensor Microwave/Imager (SSM/I) data for the Sea of Okhotsk, and have estimated the ice production for 21 years (1988–2008) by calculating heat flux from SSM/I-derived ice thickness. From a comparison with atmospheric variables, it is suggested that interannual variability of sea ice production in the polynyas can be explained mainly by three atmospheric parameters: autumn air temperature northwest of the sea, winter air temperature north of the sea, and late winter offshoreward wind speed north of the sea. By using these parameters from atmospheric reanalysis data, the annual ice production for the 34 years period from 1974 to 2008 is reconstructed from a multiple regression coefficient analysis. The reconstructed ice production shows a significant decreasing trend of ~11.4% over 34 years, which is mainly explained by the warming of autumn air temperature. It is also found that the variation in the annual total ice production corresponds well with the potential temperature variation in Okhotsk Sea Intermediate Water (OSIW). This first observational evidence of a linkage between the annual total ice production and OSIW supports a hypothesis that decreasing ice production in the Okhotsk coastal polynyas, at least in part, has led to weakening of the overturning in the North Pacific.

Introduction

The Sea of Okhotsk is the southernmost sea in the Northern Hemisphere with a sizable seasonal sea ice cover. During autumn and winter, prevailing northwesterly wind transports very cold air over the sea from the Cold Pole, where the lowest air temperature in the Northern Hemisphere is recorded. As the result, sea ice cover is extensive in the Sea of Okhotsk in spite of its relatively low latitude (Nihashi et al., 2009). In the northern part of the Sea of Okhotsk, areas of thin ice (coastal polynyas) are formed by divergent ice motion associated with the prevailing northwesterly wind. In particular, the northwestern shelf (NWS) region (Fig. 1) is a huge coastal polynya in the Sea of Okhotsk (Martin et al., 1998; Kawaguchi et al., 2010). Because the heat insulating effect of sea ice is greatly reduced where the ice is thin, the total heat flux to the atmosphere in the polynya is one or two orders of magnitude larger than that in the surrounding area of thicker ice (Maykut, 1978). Hence, sea ice is formed actively in coastal polynyas.

High ice production in the Okhotsk coastal polynyas leads large amounts of brine rejection, and dense shelf water (DSW) is subsequently formed (Shcherbina et al., 2003). Several numerical studies have successfully reproduced DSW formation associated with sea ice production in the Sea of Okhotsk (Matsuda et al., 2009; Sasajima et al., 2010; Fujisaki et al., 2011; Uchimoto et al., 2011). The DSW is transported southward via the East Sakhalin Current (Gladyshev et al., 2003; Fukamachi et al., 2004) and then mixed with intermediate water entering the sea from the North Pacific through the northern Kuril straits, and thereby Okhotsk Sea Intermediate Water (OSIW) is formed (Wong et al., 1998; Itoh et al., 2003). OSIW is considered the main ventilation source of the North Pacific Intermediate Water (Talley, 1991; Warner et al., 1996). In this way, sea ice production in the Okhotsk coastal polynyas drives the overturning in the North Pacific down to intermediate depths

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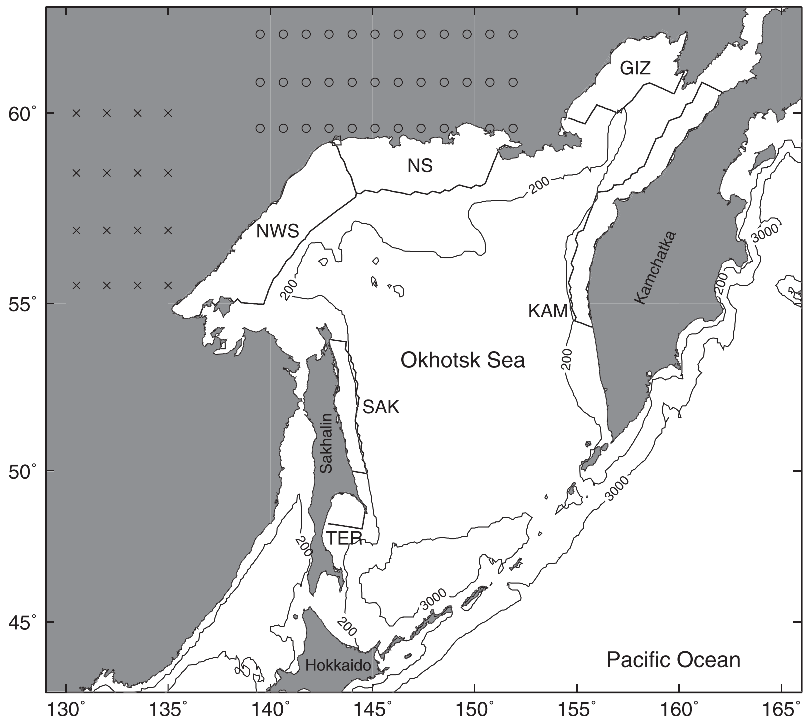

Fig. 1. Map of the Sea of Okhotsk with the polynya boxes used in the calculation. Abbreviations are as follows: NWS, northwestern shelf; NS, north shelf; GIZ, Gizhiga Bay; KAM, western Kamchatka coastal region; SAK, northeastern Sakhalin; TER, Terpenia Bay. Crosses and circles indicate the atmospheric data grid points used in 'Comparison with atmospheric variables'. The 200- and 3000-m isobaths are indicated by thin contours.

(to approximately 200–800 m depth). This overturning can contribute to the material cycle and the subsequent biological productivity through the supply of nutrients such as iron (Nishioka et al., 2007). Therefore, to understand the climate system in the North Pacific, quantitative estimation of sea ice production in the Okhotsk coastal polynyas is important.

During the past 50 years, the intermediate layer (between 26.8 and 27.0 σ_θ isopycnal surfaces) in the North Pacific has warmed, and its dissolved oxygen content has decreased (Ono et al., 2001; Nakanowatari et al., 2007). Nakanowatari et al. (2007) showed that these changes originated in the Sea of Okhotsk and suggested that the overturning in the North Pacific has weakened. Because air temperature on the windward side of the Sea of Okhotsk has been warming and the sea ice extent in the Sea of Okhotsk has been decreasing, they have hypothesized that the cause of the weakening of the overturning is a decrease in the production of DSW in the Okhotsk coastal polynyas.

DSW formation in winter associated with ice production in the Okhotsk coastal polynyas was directly observed by moorings (Shcherbina et al., 2003, 2004a,b; Fukamachi et al., 2009), and hydrographic observations in spring have confirmed the water property changes associated with DSW formation (Gladyshev et al., 2000). However, the relationship between ice production and variation of the OSIW has not been discussed on the basis of observation, except by Gladyshev et al. (2000), which compared the ice production and hydrographic data on the northwestern shelf in 1996 and 1997. Nakanowatari et al. (2007) used the ice extent as an index of ice production. However, the ice extent depends also on the temperature of water inflowing from the Pacific (Nakanowatari et al., 2010); thus, the ice extent may not be an adequate measure of ice production.

Ice production in coastal polynyas has been estimated by heat flux calculations using sea ice information from the passive microwave radiometers, which can observe the sea surface regardless of darkness or cloud cover. A sea ice production map in the Sea of Okhotsk was shown by Ohshima et al. (2003), in which an ice type algorithm for Special Sensor Microwave/Imager (SSM/I) data (Kimura and Wakatsuchi, 1999) was used with heat flux calculations. Martin et al. (2004) developed a thin ice thickness algorithm for SSM/I in the Chukchi Sea coastal polynya by comparing with ice thickness estimated from clear-sky Advanced Very High Resolution Radiometer (AVHRR) infrared images. Then, they estimated the ice production from heat flux calculations using SSM/I-derived ice thickness. Tamura et al. (2008, 2012) estimated ice production in Antarctic coastal polynyas using a similar method based on SSM/I-derived ice thickness. In the Sea of Okhotsk, Nihashi et al. (2009) developed a thin ice thickness algorithm for Advanced Microwave Scanning Radiometer-EOS (AMSR-E) at a higher spatial resolution, based on a comparison with AVHRR-derived ice thickness. This AVHRR-derived ice thickness was validated by ice thickness measurements from an ice profiling sonar in the Sakhalin polynya (Fukamachi et al., 2009). This validation guarantees a certain level of accuracy in the ice thickness estimation. However, because AMSR-E data are available only for 2003–2010, longer-term analysis of sea ice production is not possible using only from AMSR-E data.

In this study, we developed a thin ice thickness algorithm for SSM/I data, which are available from 1987. By using this SSM/I-derived ice thickness, we estimated ice production in the Okhotsk coastal polynyas during the winters from 1988 to 2008. We then compared the annual total ice production with atmospheric parameters to examine the factors that influence the interannual variation in sea ice production. Further, we used the atmospheric data set to reconstruct the ice production over a longer period (1974–2008). Finally, on the basis of our findings, we examined the relationship between sea ice production and the OSIW.

Data

We used daily mean SSM/I brightness temperatures provided by the National Snow and Ice Data Center (Maslanik and Stroeve,