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What drives the southward drift of sea ice in the Sea of Okhotsk?

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ABSTRACT

The Sea of Okhotsk is the southernmost sea-ice zone with sizable ice. It is widely believed that the prevailing northwesterly wind and the southward East Sakhalin Current (ESC) are the two main factors that drive the southward drift of sea ice. However, the relative contributions of these factors have not been understood. In this paper, by using the current and ice-drift data measured with the moored Acoustic Doppler Current Profiler, a 3-D ocean model simulation, objective analysis data of the wind, and satellite sea-ice data, we examine to what degree and how the ice drift is determined by the wind and ocean current. From a linear regression of the observed ice drift, ocean current, and wind, the wind-forced component of the ice drift was best fitted when sea ice is assumed to move with a speed of 1.6% of the geostrophic wind with a turning angle of 17.6° to the left of the wind. Such a relationship was adopted as the wind-drift component for all sea-ice pixels detected from Special Sensor Microwave Imager data. For the ocean-forced component of the ice drift, we adopted the current at 20 m depth from a numerical model simulation that reproduces well the ESC and its variability. We then evaluated the sea-ice drift over 46–54°N during 1998–2005. For the southward drift of sea ice, the contribution of the wind component is found to be larger than the oceanic component, although the ocean contribution becomes larger, typically comparable to the wind contribution, near the coast and in the northern region where the ESC is stronger. We estimated the average annual cumulative southward ice transport to be $3.0 \pm 0.9 \times 10^{11}$ m^3 at 53°N. This ice transport is comparable to the annual discharge of the Amur River. The ratio of wind to oceanic components in the transport is estimated to be ~1.2–1.8. We also conducted ice-drift simulations based on the modeled current velocity and the assumed wind drift of 1.5% geostrophic wind with a turning angle of 15° to the left. The simulations reproduce well the ice drift north of 47°N but not south of 47°N, likely due to the poor representation of the current system at the latter, underevaluation of the wind factor near the ice edges, and the neglect of ice formation and melt.

Introduction

In the Northern Hemisphere, the Sea of Okhotsk is the southernmost sea with a sizable seasonal ice cover. The primary cause for this is the advection of very cold air from the cold pole of the Eurasian continent (Nihashi et al., 2009). The southward extension of sea ice is further enhanced by the prevailing northwesterly wind and southward ocean current. Watanabe (1963), who first investigated the mechanism of the southward transport of sea ice, examined the relationship between ice thickness and the ice growth rate and speculated that the sea ice off the northern Hokkaido coast originates from off the northern part of the Sakhalin coast. From the estimated mean southward ice drift of 0.3–0.5 m s^{-1}, Watanabe (1963) estimated the contribution of the wind ice drift to be 0.1 m s^{-1} and regarded the residual of 0.2–0.4 m s^{-1} to come via a southward ocean current known as the East Sakhalin Current (ESC). Mochizuki et al. (1995) reported the first direct observations of ice drift in the Sea of Okhotsk by tracking buoys deployed on ice floes, which showed that ice floes drifted southward at a speed of ~0.35 m s^{-1}.

Kimura and Wakatsuchi (1999), using Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) sea-ice data, showed that the speed of ice-edge advance is about 2% of the geostrophic wind. The relationship of the wind factor and turning angle of Okhotsk sea ice to the geostrophic wind was investigated by using the maximum cross-correlation method with SSM/I data (Kimura and Wakatsuchi, 2000). The ocean current

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was regarded as a constant component in their study. They concluded that the wind factor in the Sea of Okhotsk is 2%, which is consistent with the estimated ice-edge advance. The turning angle is roughly zero within ±10°, and the direction of ice drift is almost parallel to that of the geostrophic wind. However, in the southernmost sea-ice area south of Sakhalin Island, the correlation between the wind and ice drift is low, and the wind factor is small (Kimura and Wakatsuchi, 2000).

Although the sea ice was considered to drift southward because of the ESC (Watanabe, 1963), the ESC was not well understood because there had been very few direct observations. Intensive surface drifter observations revealed an ESC width of 150 km and speed of 0.2–0.4 $\mathrm{m\,s^{-1}}$ (Ohshima et al., 2002). The observations further suggest that the ESC has two components: a nearshore component that reaches off Hokkaido and an offshore component that is a part of the cyclonic gyre. Mooring array observations revealed a prominent seasonal variation of the ESC, with the largest southward velocity and transport occurring in winter (Mizuta et al., 2003).

When we consider the dynamical balance of sea ice on a time scale longer than one day, the ice drift is determined mainly by wind, ocean, and internal stresses. When the condition of free drift is met, and sea-ice concentration is less than about 90%, internal stress is negligible (Thorndike and Colony, 1982; Leppäranta, 1998, 2005). In this case, the ice drift is determined by stresses from the wind and ocean. In the case of the Sea of Okhotsk, the southward ice drift is determined by the northwesterly monsoon and the ESC.

A large amount of ice advection from the north to the south leads to the transport of freshwater and negative heat via latent heat. Ohshima et al. (2003), on the basis of a heat budget analysis with SSM/I sea-ice data, showed that the annual net heat flux exhibits a clear regional contrast: a large negative flux (sea or sea ice loses heat to air) in the northwestern region and a positive flux in the southern region. They concluded that part of this contrast is caused by the southward transport of negative heat by the sea-ice drift. Furthermore, Nihashi et al. (2012) created an improved higher-resolution heat/salt flux dataset associated with sea-ice growth and melting. For the heat flux, a result similar to Ohshima et al. (2003) was obtained, and for the salt flux, the annual mean salt flux to the ocean was positive in the northern area and negative in the southern area. The negative salt flux in the south indicates ice melt, whose freshwater flux is comparable to the Amur discharge of $\sim 3 \times 10^{11}\ \mathrm{m^3\,year^{-1}}$. This contrast between the north and south means that a considerable amount of freshwater is transported southward by sea ice. Fukamachi et al. (2009) directly measured ice thickness and drift speed in the coastal region off northeastern Sakhalin and estimated that the southward transport of freshwater by ice advection is $3.1\text{–}7.3 \times 10^{11}\ \mathrm{m^3}$, which is comparable to or larger than the Amur discharge.

The southward sea-ice drift and its role in freshwater transport were investigated by using a coupled ice-ocean model (Watanabe et al., 2004). In this model, the mean southward speed of the sea-ice area is 0.31 $\mathrm{m\,s^{-1}}$, and the contribution of the ocean current to the ice drift is twice as large as that of the wind. Sea ice melts at the ice edge even in mid-winter. The annual freshwater flux to the sea surface due to sea-ice melt is $11.6 \times 10^{11}\ \mathrm{m^3}$, which is 3.5 times the annual Amur discharge.

Recent numerical model studies have approximately reproduced the structure and seasonal variability of the ESC. Simizu and Ohshima (2006) were the first to develop a moderate resolution ($1/6° \times 1/6°$) model that can reproduce the nearshore and offshore components of the ESC with their seasonal variations. They further showed that this model could reproduce the synoptic variation of the ESC observed by moorings and surface drifters. However, the model did not incorporate the influence of the Amur discharge. Moreover, a drawback of the model is that water exchange with the Japan Sea and the Pacific through the straits is not included. Uchimoto et al. (2007) developed a more realistic model with a resolution of $1/12° \times 1/12°$ that includes water exchange with the Pacific and Japan Sea. Ono et al. (2013) further improved the model of Uchimoto et al. (2007) by making the vertical resolution finer near the sea surface, which enhanced the model's agreement with observations. Fujisaki et al. (2007) used the ocean current from the model by Uchimoto et al. (2007) for short-term predictions of sea-ice cover in the southern Okhotsk Sea and approximately simulated the ice edge location.

The primary purpose of this study is to clarify the contributions of the wind and ocean components to the ice drift, based on mooring observations of ocean and sea ice, the modeled ocean current, and the geostrophic wind derived from objective analysis data. As previously described, although the southward ice drift in the Sea of Okhotsk is caused by the wind and the ocean current, the precise contributions of the two components have not been identified. To estimate these contributions, we primarily used simultaneous observations of ice drift and ocean current. By comparing these observations, we evaluated the ocean drift component derived from the modeled ocean current and the wind drift component derived from a geostrophic wind calculation along the east Sakhalin coast. From these ice-drift estimates, the heat and salt fluxes were also estimated by calculating the volume transport of sea ice, which is a supplemental purpose of this study. Finally, we conducted particle-tracking experiments using the modeled ocean current and the calculated geostrophic wind, which provide a basis for the development of a sea-ice prediction model.

Estimation of the wind and ocean drifts

To accurately evaluate the ocean and wind components of the southward ice drift, simultaneous observations of the ice drift and ocean current are indispensable. Such observations have been conducted by Acoustic Doppler Current Profiler (ADCP) moorings at several stations in the Sea of Okhotsk (Mizuta et al., 2003; Fukamachi et al., 2009). These observations provide an accurate estimate of the wind factor and turning angle for the wind ice drift because the ice drift and ocean current were observed at the same time. If the values of these parameters are applied to the entire Okhotsk Sea, the wind drift component can be obtained by using the geostrophic wind over the sea. In contrast, the ocean drift component is much more difficult to evaluate because the ocean current exhibits large spatial variability. However, recently developed numerical models can reproduce well the ocean currents, including the synoptic variability, at least in the ESC region of southward ice-drift (e.g., Ohshima and Simizu, 2008; Ono et al., 2013). A combination of the wind drift component derived from the geostrophic wind with the appropriate parameters and the ocean drift component derived from the high-performance numerical model will provide the ice-drift dataset over the entire sea. This section describes the details of these components.

Wind factor and turning angle

In this paper, the sea-ice velocity (U, V) is defined by the geostrophic wind velocity (u, v) and surface-ocean current (c_u, c_v). The sea-ice velocity can be written as

$$\begin{pmatrix} U \\ V \end{pmatrix} = F \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} u \\ v \end{pmatrix} + \begin{pmatrix} c_u \\ c_v \end{pmatrix}, \qquad (1)$$

where F is the wind factor and θ is the wind turning angle to the left (Leppäranta, 2005).