UNDERSIDE PROFILE AND DRIFT CHARACTERISTICS OF SEA ICE ON THE JAPANESE COAST OF OKHOTSK SEA

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ABSTRACT

Okhotsk Sea coast of Hokkaido, Japan, is known as the southern limit of sea ice, which forms in high-latitude waters and arrives at Hokkaido between January and March every year. In this study, observation was conducted using IPS (Ice Profiling Sonar) and ADCP (Acoustic Doppler Current Profiler), which have been adopted in recent years. As a result of analyzing data obtained in February 2001, sea ice mainly moved in a southeast direction along the coast, and the traveling speed was approximately 0.2 m/sec. A high correlation was observed between the traveling speed of sea ice, wind velocity and velocity of current in ocean. The cross section of sea ice passing over the equipment was also estimated by the draft and traveling speed. The maximum draft observed was 3.6 m, and the frequency of drafts of 2 m or deeper was 4 % and those of 3 m or deeper was 0.1 %. It was confirmed that large-scale deformed ice formed by dynamic actions existed even in Okhotsk Sea coast of Hokkaido.

INTRODUCTION

When designing and constructing offshore/coastal structures, pipelines and other underwater and buried structures or conducting transport by sea vessels in ice-infested waters, interaction with sea ice must be fully taken into consideration. It is also necessary to acquire information on the underside profile of sea ice, ice thickness distribution and other matters in advance for prediction of oil spreading or recovery of oil in the event that a spill occurs in ice-infested waters. In particular, with the recent progress of oil and natural gas development along the Sakhalin continental shelf, transport of oil and natural gas to Japan by pipelines and vessels as well as accompanying oil spills or other accidents are expected in the future. Clarification of ice conditions in Okhotsk Sea coast of Hokkaido and other engineering studies concerning the above issues will therefore be increasingly necessary. Because hardly any field observation has been conducted in Okhotsk Sea coast of Hokkaido (Fig. 1), we have conducted sea ice surveys using ADCP (Acoustic Doppler Current Profiler) and IPS (Ice Profiling Sonar) since 2000, which have been adopted in recent years. Some results of our surveys have already been reported (Hayakawa, et al., 2001; Sakikawa, et al., 2002). Another sea ice surveys using a similar method are also being conducted in the northeastern Sakhalin (Birch et al., 1999).

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The purpose of this study is to investigate and clarify the underside profile, ice draft and behavioral characteristics of sea ice or the extent of influence of the shear stress of wind and current in ocean on the sea ice motion. They are extremely important basic data for studying the above issues in the specified area.

**SURVEY METHOD**

**Outline of survey**

The observation site was 2.4 km off the coast of Mombetsu, Hokkaido. A Doppler-type multi-layered current meter (WH-ADCP manufactured by RD Instrument, U.S.A., hereinafter referred to as ADCP) and an ice profiling sonar (IPS-4 manufactured by ASL, Canada, hereinafter referred to as IPS) were installed at a depth of 18 m for continuous observation of the draft and traveling speed of sea ice passing over the observation equipment. Both ADCP and IPS are measuring instruments using ultrasonic waves, and were placed approximately 250 m away from each other as shown in Fig. 2 to avoid interference with ultrasonic waves transmitted from each instrument.

**Observation equipment**

**ADCP (Acoustic Doppler Current Profiler)**

ADCP transmits ultrasonic waves in four directions at an angle of 30 degrees from the vertical. It receives waves reflected from plankton and other matter in water and measures the flow velocity/direction in each measurement layer from the difference of frequency caused by the Doppler effect. The bottom tracking function can be added to ADCP, by which the traveling direction/speed of sea ice and velocity of current in ocean were measured. In this study, we used the current velocity/direction at water depth 6.25m. The principle of ADCP is described in detail by Sakikawa et al. (2002), Belliveau et al. (1989) and Birch et al. (1999).

**IPS (Ice Profiling Sonar)**

IPS transmits ultrasonic waves of 430 kHz vertically upward from its body, and measures the distance from the arrival time of reflection waves from the underside of sea ice. The distance to the water surface is also measured by the built-in water pressure gauge. The draft of sea ice can therefore be estimated from the difference between these two distances. The built-in sensor measures the water temperature and inclination of the body simultaneously and corrects data. IPS was installed at approximately 1.5 m above the sea.
floor by the float suspension method by fixing four buoys to its body. Its general principle is described in detail in the report by Birch et al. (1999).

Tide level and wind direction/velocity

The tide level and wind direction/velocity data used in this paper were obtained at the inner part of the Mombetsu Port located approximately 5 km northwest of the observation site (see Fig. 2). The wind velocity was measured at 18m above ground level.

Here, the methods for measurement and processing for above data used in this study were summarized in Table 1.

<table>
<thead>
<tr>
<th>Item</th>
<th>Equipment/type</th>
<th>Measured point</th>
<th>Measurement interval</th>
<th>Data processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draft of sea ice</td>
<td>IPS</td>
<td>-</td>
<td>1 sec.</td>
<td>10-sec. mean value</td>
</tr>
<tr>
<td>Direction/speed of sea ice</td>
<td>ADCP</td>
<td>-</td>
<td>10 min.</td>
<td>10-min. mean value</td>
</tr>
<tr>
<td>Current direction/velocity</td>
<td>ADCP</td>
<td>-6.25m</td>
<td>10 min.</td>
<td>10-min. mean value</td>
</tr>
<tr>
<td>Wind direction/velocity</td>
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<td>1 hr.</td>
<td>10-min. mean value</td>
</tr>
<tr>
<td>Tide level</td>
<td>Floating type</td>
<td>-</td>
<td>1 hr.</td>
<td>1-hr. mean value</td>
</tr>
</tbody>
</table>

**OBSERVATION RESULTS**

**Characteristics of sea ice motion**

Figure 3 shows the locus of sea ice motion two-dimensionally, from the traveling speed and orientation of sea ice measured by ADCP between February 8 and 19, 2001, when sea ice existed at the observation site (the figure does not show the sea ice motion essentially). It was impossible to obtain data by IPS on and after February 20 (for an unknown cause). From the figure, it can be seen that sea ice moved southward along the coast during this period.

Figure 4 shows the time series of the traveling speed of sea ice, current (–6.25 m) and wind velocity. The traveling speed of sea ice was 0.2 m/s on average. Figure 5 shows the orientation of sea ice motion, current and wind. Where, the direction of the movement from north to south is represented as 0° and the clockwise rotation is assumed to be positive. The two figures show that the sea ice motion depends greatly on the current and wind. It is generally considered that shear forces by wind and current, Coriolis force, the force due to the inclination of sea surface and ice internal force (mutual intervention force by mutual collision and contact of ice) are the factors that control sea ice motion. In this study, only the correlation among the traveling speed of ice \( V_i \), wind velocity \( V_w \) and current (ocean stream) \( V_c \) was investigated because the sampling intervals for the traveling speed data of sea ice were long and other information was lacking. The study was therefore an attempt to examine the extent of influence of the shear stress of wind and current on the sea ice motion in an indirect manner. First, the ice, wind and current velocities were resolved into vector components and the direction toward the south was regarded as the \( y \)-axis (positive). Because the \( y \)-component was large throughout the observation period, as mentioned before, the \( y \)-direction was studied here. Fig. 6(a) shows changes in normalized (average: 0, variance: 1) traveling speed of ice and wind.
velocity over time. Similarly, Fig. 6(b) shows changes in normalized traveling speed of ice and current velocity over time.

Index \( y \) represents the velocity component in the \( y \)-direction. Where, the sampling intervals of each data series were processed to be uniform (moving average processing to convert the sea ice and current velocity data at 10-minute intervals to the data at one-hour intervals) and defective data of sea ice velocity that occurred on rare occasions were deleted. Data in the same time domain of other data series were also deleted. From Fig. 6(a)(b), they can be presumed that these data correlated with each other.

To show them more quantitatively, Fig. 7 shows the cross-correlation coefficient and Fig. 8 shows the coherence calculated from cross spectrum. From these figures, a high correlation was observed among sea ice motion, wind and current, and a correlation coefficient of approximately 0.7 was obtained. Fig. 8 also shows the correlation among measured values in a certain frequency domain. Judging from these two figures, it was presumed that influence of wind on sea ice motion was slightly greater than that of current, however, while phase differences with the wind or current were expected to appear due to the inertial force of ice, a clear phase difference was not observed in this case due to the long intervals of wind sampling. A correlation was also observed between the wind and current. Although the current described as current in ocean here is
considered to include tides, fetches by the wind and density current and other currents created by unique landforms, details are currently being studied. It may also be necessary to obtain data (velocity/direction of wind and current, etc) on wide-area. Regardless of these matters, it is presumed that most of the properties of ice motion can be explained by the wind and current in Okhotsk Sea coast of Hokkaido.

**Draft and underside profile of sea ice**

Figure 9 shows the drafts of sea ice in relation to the travel distance (displacement) of sea ice, which are observed between February 8 and 19, 2001, which can be regarded as the underside profile of sea ice. The maximum draft during the observation period was 3.6 m. Drafts of over 3 m were observed several times. The travel distance was calculated as follows; the traveling speeds of sea ice at the same time as sampling of ice drafts (by IPS) were calculated by interpolation and were integrated to calculate the travel distance. The drafts were also estimated by interpolation at intervals of 1m in the travel distance. Figure 9 shows the final plotting at intervals of 3 m with moving average. The figure reveals that the underside profile of sea ice was traced over a total of nearly 180 km during this period. From these figures, it is clear that the cross section of sea ice was not flat and had very large undulations. Figure 10 shows a partial enlargement of the underside profile of sea ice, observed in a 200-m section at 9:00 a.m. and 12:00 p.m. of February 12. Of these undulations, the wedge-shaped ones projecting downward were regarded as keels. The ice thickness that froze statically (growth by heat balance) was usually up to 1 to 2 m in the northern part of the Sea of Okhotsk and up to 0.5 to 1 m in the coast of Hokkaido, and ice thicker than those is considered as deformed ice. Such developed ice fields are called hammock fields or ridge fields, and when they are individually separated, they are called drifting hummocks (ridges). Large masses of ice with a draft of over 30 m have been observed northeastern of Sakhalin. As mentioned before, information on this sea ice drafts (ice thickness) and underside profile is extremely important in relation to seabed excavation by large masses of ice (ice scour event) and interaction with structures and vessels, as well as to the forecast of diffusion and recovery of oil spills. In the latter case in particular, because development of energy resources is in progress on the continental shelf off Sakhalin, there is a possibility that the contaminated area will move southward and reach the coastal of Hokkaido if an oil spill occurs. It is necessary to estimate the underside profile of ice in advance when performing a simulation for predicting diffusion of such an oil spill. For a versatile simulation or examination, estimation of the spectrum of underside profile and/or generation of a simulation of the profile are thought to be necessary. We are developing the simulation method of underside profile using the spectrum of observed values, and the
method in which the profile is regarded as a “renewal process” taking the distribution of keel drafts and intervals of keel to account without using the spectrum. However, for a practical sense, because facial simulation of the profile is necessary, the number of observation points must be increased in the future.

Also, for statistical examination of sea ice drafts, focus was placed on drafts of 0.5 m or deeper in the data shown in Fig. 9. Their frequency distribution and exceedance probability are shown in Figs. 11(a) and 12, respectively. In this case, the occurrence rate of drafts 2 m or deeper was 4 % and that of 3 m or deeper was 0.1 %. In the observation in February 2000, a draft with a maximum depth of 6 m was observed (Hayakawa et al., 2001), and the frequency of occurrence of drafts higher than 2 m was also slightly higher than in the observation for this study.
In a practical sense, the concept of keel draft is more important than the above-mentioned draft in many cases. Here, the keel draft is assumed to be equivalent to each peak value (crest height) in Fig. 9. Figures 11(b) and 12 show the frequency distribution and exceedance probability of keel drafts. Here, the lower limit of keel draft was set at 0.5 m. Although the distribution does not differ greatly from the above-mentioned draft distribution, the frequency of appearance of keel drafts of 1 m or deeper was greater under the same condition with the lower limit of 0.5 m. Due to the reliability of data for under 0.5 m (accuracy, existence of open water surface, etc.) and the obscurity of the minimum thickness which was regarded as the keel, it was difficult to estimate the exact probability distribution. In the form of foot of the PDF (probability density function), however, the ice draft (the former case) is thought to follow the exponential distribution, while the keel draft (the latter case) equivalent to each peak value is thought to follow the extreme-value distribution.

**SUMMARY AND FUTURE WORK**

- The traveling speed of sea ice in Okhotsk Sea coast of Hokkaido was approximately 0.2 m/s on the average and 1 m/s at the maximum. Sea ice was found to move in the prevailing direction and was affected considerably by the wind and current.
- As a result of studying the underside profile of sea ice, the existence of so-called deformed ice, which was not flat and had very large undulations, was confirmed. Such undulations on the underside of ice are important basic data with regard to the seabed excavation phenomenon (Ice scour event) or forecast of oil spill diffusion.
- The frequency distribution and exceedance probability were presented for sea ice draft and keel draft. A maximum draft of over 3 m was observed according to the data of 2001 and that of 6 m was observed according to the data of 2000, indicating the existence of large masses of ice in Okhotsk Sea coast of Hokkaido.

Although there may still be inadequacies or remaining problems, certain results were obtained in this study in that new findings were obtained concerning ice conditions in the coast of Hokkaido, however, because sea ice conditions vary greatly by year and differences in area are also expected, it will be necessary to continue observation in the future to accumulate data and perform measurements at multiple points. There are also many remaining challenges, including shortening of sampling intervals for wind measurements and acquisition of wind and current data over a wide area.

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**REFERENCES**


Birch, R., Fissel, D., Melling, H., Vaudrey, K., Schaudt, K., Heideman, J. and Lamb, W.