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Variability of sea-ice draft off Hokkaido in the Sea of Okhotsk revealed by a moored ice-profiling sonar in winter of 1999

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[1] Using a moored ice-profiling sonar along with an ADCP, a spatial section of draft across 855 km of sea ice was obtained for the first time in the southwestern part of the Okhotsk Sea near Hokkaido in winter of 1999. The draft evolved from 0.20 m in mid-February to 1.45 m in late March with the overall value of 0.72 m. The draft characteristics were quite different between February and March before and after the period of strong winds. The increase of the mean draft from February to March was associated with the increase of deformed ice. The maximum draft observed was ~17 m. Ice volume was dominated by the contribution from portions of deformed ice especially in March. These results suggest that deformed ice dominated in the region of observation and dynamical processes were mainly responsible for the evolution of draft. *INDEX TERMS:* 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes; 4243 Oceanography: General: Marginal and semienclosed seas. **Citation:** Fukamachi, Y., G. Mizuta, K. I. Ohshima, H. Melling, D. Fissel, and M. Wakatsuchi, Variability of sea-ice draft off Hokkaido in the Sea of Okhotsk revealed by a moored ice-profiling sonar in winter of 1999, *Geophys. Res. Lett.*, *30*(7), 1376, doi:10.1029/2002GL016197, 2003.

1. Introduction

[2] The Sea of Okhotsk is the southernmost sea-ice area in the Northern Hemisphere except areas of coastal freezing. Sea ice first forms near the northern and northwestern coasts in November, then spreads southward along Sakhalin and eventually reaches Hokkaido typically by mid-January. Maximum ice extent normally occurs in early March. Sea-ice extent is highly variable from year to year (e.g., *Tachibana et al.* [1996]). However, annual variability has been discussed based on ice area not on ice volume due to the lack of in situ observations and remote-sensing capability for ice thickness. In fact, systematic ice-thickness observations are fairly limited in the Sea of Okhotsk. In the southwestern part of the sea, *Toyota and Wakatsuchi* [2001] carried out ship-based monitoring to measure thickness of ice floes turned into side-up positions with a downward-looking video camera in 1996–99. They showed that the average thickness in early February varied from 0.19 m in 1996 to 0.55 m in 1997. This monitoring covered most of the area off Hokkaido, however, the temporal coverage was limited and the method is not capable of measuring thick floes because they are not likely to turn into side-up positions. In the area off the northern coast of Sakhalin, *Birch et al.* [2000] carried out moored ice-profiling sonar (IPS) observations in winter of 1996–97 and 1997–98. These were the first IPS observations in the Sea of Okhotsk but a full description of the data and results is not available.

[3] In this paper, the results of the first moored IPS observation in the southwestern part of the sea during February and March of 1999 are presented. The region of observation is close to the end of ice-drift trajectories that originate in the northern part of the Okhotsk Sea. Therefore, the mooring location is suitable for observing sea ice subject to both dynamical and thermodynamical processes farther north. Purposes of this research are to report the actual values of ice draft and reveal the nature of its variability quantitatively for the first time.

[4] During winter of 1998–99, sea-ice extent over the entire Okhotsk Sea was record-breakingly large from early to mid-December, but below normal from early January to early February. The extent was above normal after mid-March and reached the maximum at the end of March. The arrival (retreat) of sea ice to (from) the coast of Hokkaido occurred later than normal.

2. Data and Processing

[5] Figure 1 shows the location of the mooring array. The array was deployed 11 km off the northeastern coast of Hokkaido (143°39′E, 44°20′N), where the water depth is 57 m. The array contained an IPS (ASL Environmental Sciences IPS4 420 kHz) and an ADCP (RD Instruments WH-Sentinel 300 kHz). The mooring duration was from December 5, 1998 to March 27, 1999. During this period, sea ice was observed by the array from mid-February to late March. Both of the IPS and ADCP were moored at 43-m depth. The IPS sampling intervals were 1 second for range and echo amplitude data and 1 minute for pressure, tilt, and temperature data. The ADCP measured ice velocity using the bottom-tracking mode as well as water-column velocity using the water-tracking mode [*Melling et al.*, 1995]. Its sampling interval was 15 minutes and the bin size for water-column velocity was 4 m. Two conductivity-temperature sensors and two thermistors were also moored at 23 and 43-m, and 33 and 49-m depths, respectively. These temperature and salinity data are used to estimate sound velocity for deriving sea-ice draft values. Atmospheric pressure data used to process the IPS data and surface wind data used to process the ADCP data were measured in Mombetsu and Yubetsu, respectively (see Figure 1 for their locations).

[6] The methods of data processing carried out in this research essentially follow previous work in the Beaufort

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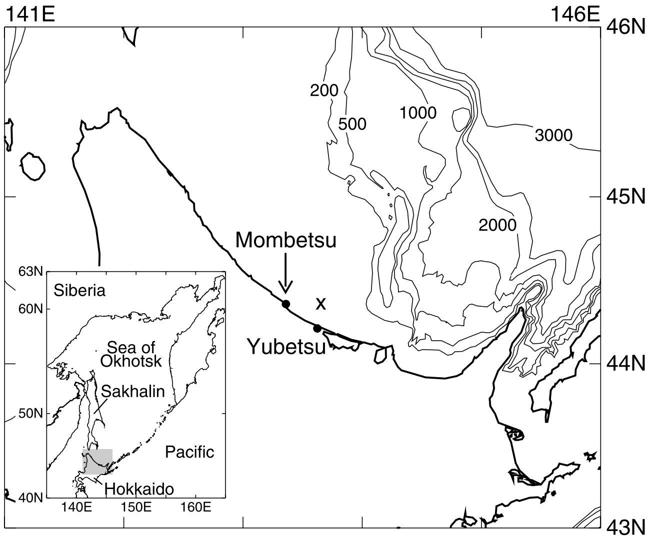

Figure 1. A map showing the location of the mooring array (denoted by a cross). The inset map shows the entire Sea of Okhotsk. The shading denotes the region of the enlarged map.

Sea [*Melling and Riedel*, 1995; *Melling and Riedel*, 1996]. General discussions on the IPS data processing are found in *Melling et al.* [1995] and *Strass* [1998], and its details are not described here. The ice-velocity data are used to convert the draft time series into the pseudo spatial series. For this purpose, a continuous time series is necessary to estimate the width of the ice-free areas and therefore ice concentration. To estimate ice velocity within data gaps, a multilinear regression of ice velocity against near-surface water velocity from the uppermost ADCP bin (6–10 m), and surface wind measured in Yubetsu is performed. The draft data discussed in the following sections are the pseudo spatial series at every 0.5 m obtained by combining the draft time series and the resultant continuous ice-velocity data. Representative values for both of the accuracy and precision of draft are ±0.05 m.

3. Results

3.1. Ice Drift

[7] Sea ice was observed at the array during the two periods from February 10 to 27 and March 6 to 27. Between these two periods, no significant ice floe was observed due to the retreat of ice edge. Figure 2a shows the alongshore and onshore-offshore components of the ice velocity. The dominance of the alongshore component clearly indicates the general southeastward drift. The cumulative displacement calculated from this time series amounts to 855 km. This length roughly corresponds to the distance between the mooring array and area off the central coast of Sakhalin assuming a path along Hokkaido and Sakhalin. The array was located in the area of the significant coastal current flowing southeastwards. This current is called the Soya Warm Current in summer, however, the warm water is absent from the upper ocean in winter. The ice velocity was well correlated with the near-surface water velocity and also affected by the local wind (shown in Figure 2b). (Values of the average scalar speed during the displayed period were about 0.17 and 0.22 m s^{-1} for the near-surface water and ice, respectively.) The ice speed varied largely in the range from nearly zero to 1.11 m s^{-1}.

3.2. Ice Draft

[8] Figures 2c to 2f show ice statistics calculated for 40-km long subsections (except for subsections 6, 7, and 18 with 25, 200, and 30 km in length, respectively) among the 855-km total path. The length of the subsections is chosen to derive draft statistics with useful confidence [*Melling and Riedel*, 1996]. The time taken to sample these subsections ranged from 0.58 (subsection 8) to 7.25 days (subsection 5). Only non-zero draft values are considered in these figures. Figure 2c shows the evolution of the mean draft for the portions of all, level and deformed ice. Here, a section of the

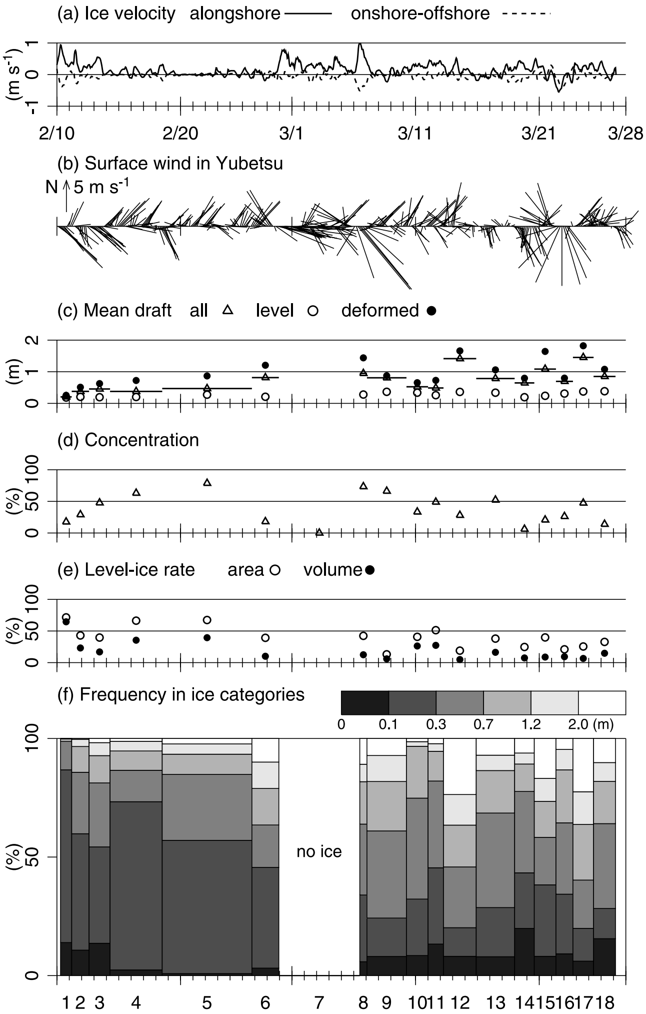

Figure 2. Time series of (a) ice velocity, (b) surface-wind vector measured in Yubetsu, (c) mean draft, (d) concentration, (e) level-ice rate, and (f) frequency in ice categories from February 10 to March 28. In (c)–(f), values are plotted for each subsection. Lengths of subsections are denoted by horizontal bars in (c) and their numbers are displayed at the bottom in (f). In (a), the alongshore and onshore-offshore components are calculated using an angle of 115°T for the local coastline orientation and the southeastward and northeastward components are positive. In (c), the mean values for all, level, and deformed ice are plotted. In (e), the level-ice rates for area and volume are plotted. In (f), ice categories are defined as shown in the gray scale.

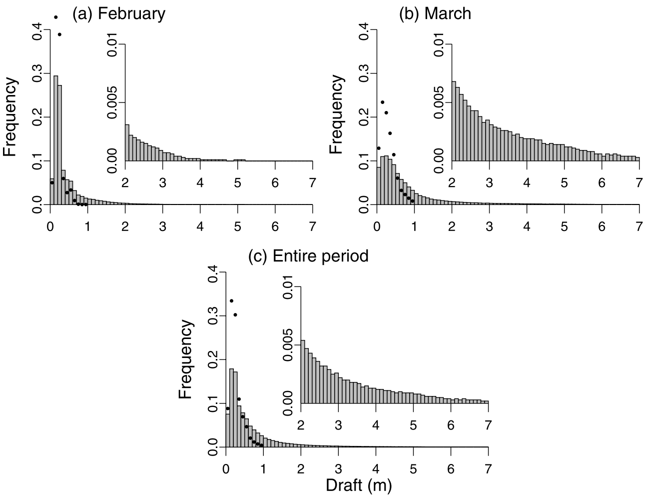

Figure 3. Frequency of draft up to 7 m in 0.1-m bins for the periods of (a) 2/10–27, (b) 3/6–3/27, and (c) 2/10–3/27. Areas of zero draft (open water) are not included. Frequency based on the portions of only level ice is also indicated with dot up to 1 m. The inset panels show the portion larger than 2 m with finer frequency resolution.

draft spatial series is classified as level ice if its draft varied by less than ±0.15 m over 10 m or longer. This more restrictive criterion than the D_2 definition in *Wadhams and Horne* [1980], which allows variations within ±0.25 m, is adopted because drafts for level ice were mostly less than 1 m (see Figure 3 below). Figure 2d displays variations of concentration evaluated by the IPS. Here, the concentration is defined as ratio between numbers of non-zero draft and all the observations for each subsection. Figure 2e illustrates the variability of level-ice rates in terms of area and volume. Figure 2f shows the change of frequency in several ice categories. The categories are for draft values of 0–0.1, 0.1–0.3, 0.3–0.7, 0.7–1.2, 1.2–2.0, and >2.0 m. The first five categories roughly correspond to those of nilas, young ice, thin, medium, and thick first-year ice, which are defined in terms of thickness.

[9] From subsections 1 to 5 (2/10–25), there was a general increasing tendency in the mean draft from 0.21 to 0.47 m with the similar tendency in ice concentration from 18 to 79%. The level-ice areal rate was initially 72% and mostly 40–70% subsequently. Its volumetric rate was initially 65% and mostly 20–40% for subsections 2–4. These level-ice rates especially in terms of volume indicate deformed ice was significant during subsections 2–4. The frequency in draft <0.3 m was initially 87% and remained over 50% subsequently, and that in draft >2 m was below 3% throughout this period. During subsections 6 and 7 (2/25–3/6), two strong atmospheric low-pressure systems passed the region of observation. As shown in Figure 2b, values of wind speed were large during this period. Values of the mean draft, concentration, level-ice rate, and frequency in ice categories changed markedly during and after these subsections. In subsection 6 (2/25–27), the mean draft increased abruptly to 0.82 m, which was accompanied by the sudden drop of concentration to 18%. The level-ice rates for area and volume dropped to 39 and 10%, respectively, and the frequency in draft >2 m increased to 10% in this subsection. These changes indicate the advection of deformed ice likely caused by the strong winds. In subsection 8 (3/6–7) after the ice-free period, the similar ice characteristics were seen except the abrupt increase in concentration to 73%. The maximum draft ~17 m over the entire record was identified and keels larger than 10 m were observed most (five) times in this subsection. After subsection 9 (3/6–27), the mean draft fluctuated largely in the range from 0.49 m in subsection 11 (3/12–13) to 1.45 m in subsection 17 (3/23–25). Note that the concentration also fluctuated largely. Subsections 10 and 11 (3/10–13) were characterized by the small mean draft (~0.5 m), high level-ice rates, and low frequency in the thickest category (<3%). On the other hand, subsections 12 (3/13–15) and 17 were characterized by the large mean draft (~1.4 m), low level-ice rates, and high frequency in the same category (>20%). These results indicate the highly variable nature of sea ice in March. Note that for the most part of March, both of the areal and volumetric level-ice rates were below 40% and 15%, respectively and the frequency in draft <0.3 m was below 40%. The decrease in the level-ice rates from February to March indicates further dominance of deformed ice in the region of observation. Note that the mean draft of level ice never exceeded 0.4 m and did not change appreciably throughout the entire period.

[10] To elucidate the overall seasonal trend in ice characteristics, its statistics are summarized before and after the strong wind period, namely in February and March. Table 1 shows draft statistics, ice concentration, and level-ice mean draft and rates for each month as well as for the entire period. The mean draft were 0.43 and 0.89 m in the two months with the overall mean of 0.72 m. Values of the standard deviation correlated with those of the mean draft. Drafts of 90, 95, 99 percentiles along with the maximum value indicate the seasonal evolution of the thicker end of sea-ice distribution. Note the fairly large values in March for these three percentiles: 10, 5, and 1% of the all observed ice exceeded draft values of 2.10, 3.31, and 5.83 m, respectively. As pointed out for Figure 2e, the level-ice rates decreased from February to March. Even in February when the areal rate was as high as 58%, the volumetric rate was only 31%. In March when the areal rate decreased to 33%, the volumetric rate

Table 1. Ice Statistics[a]

		Draft (m)							Level ice		
Period (Subsection)	Length (km)	Mean	S. D.	90%	95%	99%	Max.	Conc. (%)	Mean (m)	Area (%)	Volume (%)
2/10–27 (1–6)	225	0.43	0.50	0.98	1.44	2.57	7.29	23	0.23	58	31
2/27–3/6 (7)	200	–	–	–	–	–	–	0	–	–	–
3/6–3/27 (8–18)	430	0.89	1.17	2.10	3.31	5.83	17.02	38	0.31	33	11
2/10–3/27 (All)	855	0.72	1.00	1.64	2.60	5.19	17.02	31	0.27	42	16

[a]For the draft statistics, areas of zero draft are excluded. S.D. is the abbreviation for standard deviation. Values for 90, 95, and 99% indicate drafts that exceed these percentiles among the all the drafts sorted in increasing order.

dropped to 11%. Also note that the level-ice rates were low over the entire period as well. All of these level-ice statistics clearly indicate the importance of deformed ice more notably in terms of volume and its dominance over level ice especially in March.

[11] Figure 3 shows frequency of draft up to 7 m in 0.1-m bins for the same periods as in Table 1. Frequency values for all and level ice portions are displayed by histogram and dot, respectively. Figures 3a and 3b illustrate changes in the draft distribution quite well. Although the modal draft existed in either 0.1–0.2 or 0.2–0.3 m bin in the both of the months, frequency values in these bins dropped drastically from February to March. As the sea-ice season progressed, frequency values in the thicker drafts (shown in the inset panels) increased significantly as discussed using the statistics of the thick drafts in Table 1. The existence of drafts substantially larger than the modal drafts suggests the increased presence of deformed ice in March. Frequency of draft over level-ice portions indicates that most of the level ice was thinner than 1 m. Figure 3c shows frequency for the entire period. As a whole, thin ice with draft <1 m dominated in the frequency distribution. As indicated by the level-ice rates in Table 1, however, the contribution from thick drafts was substantial especially in terms of ice volume because the mean drafts for the level and deformed ice were quite different (see Figure 2c).

4. Discussion

[12] The variability of the observed ice draft could be caused by the thermodynamical processes, snowfall, and dynamical processes. Among these processes, the thermodynamical growth was not likely considerable because the increase in the mean draft for level-ice portions was significantly smaller than that for all ice (see Figure 2c and Table 1). Also, the effect of local snowfall was not likely significant because the largest daily snowfall during the sea-ice period was only 13 cm in Mombetsu on March 22. In fact, the decrease of the level-ice rates clearly indicates that the dynamical processes such as rafting played an important role in the evolution of ice draft. The deformed ice produced by dynamical processes resulted in 84% of the total ice volume for the entire period. The similar dominance of deformed ice in the total ice mass was previously discussed by *Melling and Riedel* [1995] in the Beaufort Sea and by *Worby et al.* [1996] in the Bellingshausen and Amundsen Seas. Although the mean draft for level ice did not change significantly, the increase of deformed ice and its draft led to the increase of the mean draft for all ice (see Figures 2c and 2e).

[13] The ice-thickness data obtained by the video monitoring [*Toyota and Wakatsuchi*, 2001] are compared with the ice-draft data obtained by the IPS. Since the former data were collected during February 3–10, the latter data during the closest period of February 10–11 (subsection 1) were chosen for the comparison. The mean values of these two data were 0.29 and 0.21 m, respectively. Considering typical density values for ice and sea water, this mean draft corresponds to thickness of 0.23 m. The rough agreement between these two thickness values obtained by the two methods suggests that the drafts obtained by the IPS are representative in the region off Hokkaido. The reason for this agreement is likely the dominance of level ice in subsection 1 (see Figure 2e). Using the SSM/I data, the average concentration in the region off Hokkaido (east of ~145°20′E and south of ~45°20′N except the nearshore region affected by land contamination) was estimated as 80 and 65% for the sea-ice periods in February and March listed in Table 1. Assuming the IPS drafts were representative in this region and using the mean drafts listed in Table 1, the average ice volume in this region during March was estimated to be ~1.7 times as large as that during February.

[14] In this research, the evolution of sea-ice draft is documented for the first time in the southwestern part of the Okhotsk Sea and the highly variable nature of sea ice dominated by deformed ice is revealed. However, it is obvious that the accumulation of more data is necessary to enhance our understanding of the nature of ice thickness (and volume) since this research is solely based on the data at a single point during one winter. The accumulation of in situ data will also provide the indispensable sea truth for methods to estimate ice thickness using remote-sensing data (e.g., *Tateyama and Enomoto* [2001]). Moreover, combining the drift information derived from the sea-ice radar data in the region near Hokkaido (e.g., *Tabata et al.* [1969]) with the IPS data should enable us to identify the location of deformation for the deformed ice observed at the IPS.

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