Polar Meteorol. Glaciol., **14**, 58–67, 2000

Estimation of the volume of sea ice cover in the Sea of Okhotsk and related atmospheric conditions for 1991/92–1998/99 winters

Kazutaka Tateyama[1,2] and Hiroyuki Enomoto[1,3]

[1] *Department of Civil Engineering, Kitami Institute of Technology, 165, Koen-cho, Kitami 090-8507*
[2] *Okhotsk Sea Ice Science Research Co. Ltd., 25-2, Moto-Mombetsu, Mombetsu 094-0023*
[3] *Frontier Observational Research System for Global Change*

Abstract: The volume of sea ice cover in the Sea of Okhotsk during 1991/92–1998/99 winters (December–April) was estimated by using SSM/I data sets with the S/KIT algorithm (Tateyama *et al.*, Bull. Glaciol. Res., **17**, 23, 2000) which can distinguish among fast ice, floes, young ice, new ice and multi-year ice types. The variability in the yearly ice production is discussed in association with daily mean air temperature and winter mean sea level pressure.

Areas of less ice appeared in the winters of 1995/96 and 1996/97, during which ice cover was 75% and 69%, respectively, of the maximum ice area ($1.25\times10^6\,km^2$) in the winter of 1997/98. The ice volumes in the winters of 1995/96 and 1996/97 decreased by as much as 58% and 56%, respectively, of the maximum ice volume ($5.5\times10^2\,km^3$) in 1994/95. Furthermore, the mean ice thickness, calculated by dividing the ice volume by ice area of the whole Okhotsk Sea, was thinner in winters when the ice area was small. The ice volume was correlated with cold air conditions, especially off the northeast coast of Kamchatka, where air temperature is affected greatly by the Aleutian low. The winter mean sea level pressure showed that ice volume was small when the Aleutian low was strong.

1. Introduction

Knowledge of the volume of sea ice cover is of particular importance and interest for meteorologists, oceanographers and biologists to understand processes of heat flux, brine formation and dense water production. Most previous studies have provided knowledge on ice extent and ice concentration estimated from satellite images. Quantities of ice extent and concentration have been derived from the single channel microwave radiometer ESMR launched in 1972. Although the single channel microwave radiometer has suggested a possible multi-year ice category, the algorithm did not determine whether a change in microwave was due to concentration change or ice type change. The ice concentration and classification of ice type, such as first-year ice or multi-year ice, have been done separately since the multichannel microwave radiometer SMMR was launched in 1978. Since 1987 the Special Sensor Microwave/Imager (SSM/I) has been in practical use.

Wensnahan *et al.* (1993) introduced an empirical equation for thin ice analysis using principal component analysis (PCA), and proved that thin ice can be detected using the SSM/I sea ice data in the Bering Sea over one day. Cavalieri (1994) suggested an algorithm named the NASA team thin ice algorithm for thin ice detection, which uses the SSM/I data and makes it possible to distinguish among new, young and first-year ice types in seasonally ice covered areas. Tateyama *et al.* (2000) established a new algorithm which can classify ice types, *i.e.* fast ice, floes, young ice and new ice, with a higher spatial resolution ($12.5\times12.5\,\text{km}^2$) than the NASA team algorithm ($25\times 25\,\text{km}^2$). This new algorithm uses the 85-GHz SSM/I channel, which has finer spatial resolution than the other SSM/I channels. This algorithm was named the S/KIT algorithm.

The ice volume, however, was not estimated until the ice thickness was derived from satellite data. We attempted to obtain the ice thickness by analyzing the relationship between the thickness parameter $R_{37V/85V}$ and satellite visible and near-infrared images. The relationship was validated with ship-based ice thickness measurements by the icebreaker "Soya" (Tateyama and Enomoto, 2000). Ice thicknesses were assumed to be 1–10 cm (new ice), 11–34 cm (young ice), 35–85 cm (floes) and 86–120 cm (fast ice), respectively, related to the variations of $R_{37V/85V}$.

The purpose of this study is to investigate the relationship between the volume of sea ice cover and atmospheric conditions in and around the Sea of Okhotsk. We first obtain ice thickness from the SSM/I satellite data with the S/KIT algorithm and estimate the volume fluctuation in the ice covered area in the Sea of Okhotsk for 1992–1999 winters (December–April). We also consider the effects of meteorological conditions on yearly ice production.

2. Data and sampling area

The daily brightness temperatures derived from DMSP SSM/I, which has vertically and horizontally polarized 19-GHz, 37-GHz, 85-GHz channels and a vertically polarized 22-GHz channel, were obtained from the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, USA. From those brightness temperatures, the ice concentration was calculated with the NASA team algorithm (Cavalieri, 1994), using the coefficients for the Sea of Okhotsk developed by Enomoto (1996). Ice thickness is provided by the S/KIT algorithm (Tateyama *et al.*, 2000) based on the radiometric properties of the sea ice surface using 37-GHz and 85-GHz channels. The ice thickness parameter $R_{37V/85V}$, defined as a ratio between the brightness temperature (T_B) of the vertically polarized 37-GHz (T_{B37V}) and T_B of the vertically polarized 85-GHz (T_{B85V}) in the S/KIT algorithm, was used in this study. $R_{37V/85V}$ increases with increase in ice thickness or snow depth over the ice layer in the packed ice area. T_{B85V} varies in the same way as ice surface temperature, while T_{B37V} has a relatively constant value because the penetration depths of T_{B85V} and T_{B37V} in first-year ice are below 1 cm and about 3 cm, respectively. Ice thickness is estimated to be thin because T_{B85V} is large, meaning that ice temperature in the surface layer is high, as $R_{37V/85V}$ is small, and *vice versa.*

The value of $R_{37V/85V}$ is sensitive for open water signals, thus it may cause errors for less than 100% concentration sea ice area. Ice thicknesses using $R_{37V/85V}$ values are calculated in pixels that not only having 100% ice concentration but also expanding greater than 80%. This is because the lower ice concentration area in the Okhotsk Sea is a small part of the total ice covered areas, then their accumulated error seems to be

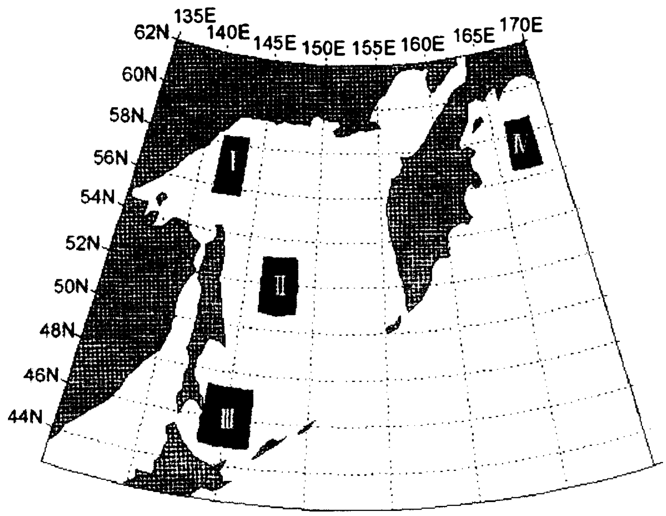

Fig. 1. Map of the Sea of Okhotsk. Shadowed areas (I, II, III, IV) on the sea cover sampling sites for air temperature at 700 hPa and sea level pressure.

not large. And also this is because of uncertainty of estimated ice concentration values in over 80% concentration. There is still uncertainty (*ca.* 10% or more for new and young ice areas) in the present available algorithm, such as the NASA team thin algorithm for Okhotsk Sea. Although this study applied new algorithm to the sea ice area over 80% in ice concentration, it may not cause the serious error for indicating the characteristics of ice type fluctuation.

The SSM/I data have been available since 1987, except for the 85-GHz channels data between 1989 and 1991. Hence the volume of ice cover in the Sea of Okhotsk was estimated using the S/KIT algorithm from December 1991 to March 1999 in this study. We defined winter as the 5 months from December to April.

Figure 1 shows the observation areas of ice volume and air temperatures at 700 hPa height and sea level pressure in the Sea of Okhotsk. The meteorological data used in this paper are the NCEP/NCAR reanalysis data from the NOAA-CIRES Climate Diagnostics Center, daily averaged and gridded every 2.5° in both latitude and longitude.

3. Estimation of ice thickness and volume

The total 'ice extent' (E_{total}) can be calculated by summing the number of pixels (E_{local}) in which the ice signal indicates that ice concentration exceeds 80% within the pixel ($12.5 \times 12.5\,\mathrm{km}^2$). The total 'ice area' is then calculated by summing the local ice extent (E_{local}) multiplied by local ice concentration (C_{local}).

$$E_{\mathrm{total}} = \Sigma\,(E_{\mathrm{local}}), \tag{1}$$
$$A_{\mathrm{total}} = \Sigma\,(E_{\mathrm{local}} \times C_{\mathrm{local}}). \tag{2}$$

The 'ice volume' was defined as the volume of ice covered area and was used to

Table 1. Threshold values of $R_{37V/85V}$ for four ice types, area of lower concentration than 80% and open water.

Categories	Thickness	Threshold Values
Fast ice	86-120 cm	$1.12 \leqq R_{37V/85V}$
Floes	35-85 cm	$1.00 \leqq R_{37V/85V} < 1.12$
Young ice	11-34 cm	$0.97 \leqq R_{37V/85V} < 1.00$
New ice	1-10 cm	$0.92 \leqq R_{37V/85V} < 1.00$ and $0.20 \leqq R_{19H/85V} < 0.30$
Low concentration	1-50 cm	$0.92 \leqq R_{37V/85V} < 0.97$
Open water		$R_{37V/85V} < 0.92$

discuss the change in ice quantity as the ice concentration, the ice edge extends and retreats easily by action of winds and ocean currents. The ice volume was simply calculated as the product of ice area and ice thickness for each pixel. The ice thickness was classified into several types based on the parameter $R_{37V/85V}$, as shown in Table 1. Ice thickness h is calculated using the following equation (Tateyama and Enomoto, 2000);

$$h = h_0 + h_C\ (R_{37V/85V} - R_H), \tag{3}$$

where h_0 is the minimum thickness of each ice type, 1 cm, 11 cm, 35 cm and 86 cm for new ice, young ice, floes and fast ice, respectively. These minimum thicknesses were obtained from ship-based measurements in the Sea of Okhotsk by the icebreaker "Soya". h_C is a constant, which is calculated by the range in thickness divided by $R_{37V/85V}$ (maximum) minus the threshold values R_H of each ice type. In the case of floes, for example, h_0, h_C and R_H are 35, 454.5, 1.00, respectively. Thickness of 'low concentration' ice ranged from 1 cm to 50 cm, which was regarded as thin ice; such thin ice can always be seen in the marginal ice zone, consisting of new ice and broken ice in the freezing season. The contribution of low concentration ice to total ice extent or ice area is low in the maximum ice extent season.

Total ice volume V_{total} was calculated as

$$V_{total} = \Sigma\ (A_{local} \times h_{local}), \tag{4}$$

where A_{local} and h_{local} are ice area and ice thickness in each pixel, respectively.

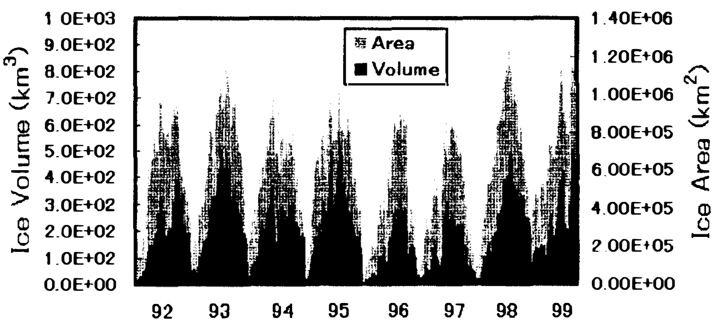

Fig. 2. The daily fluctuation in ice area and volume during winters (December-April) for 1992-1999.

Figure 2 shows ice area and ice volume during December–April for 1991/92–1997/98 and December–March for 1998/99. The average ice area and volume were $0.60 \times 10^6 \mathrm{km}^2$ and $1.9 \times 10^2 \mathrm{km}^3$, respectively, in this period. Large ice volumes were seen in the winters of 1992/93, 1994/95 and 1997/98. Areas of less ice appeared in the winters of 1995/96 and 1996/97, with 75% and 69%, respectively, of the maximum ice area ($1.25 \times 10^6 \mathrm{km}^2$) in winter 1997/98. Ice volumes in the winters of 1995/96 and in 1996/97 decreased by as much as 58% and 56% of the maximum ice volume ($5.5 \times 10^2 \mathrm{km}^3$) in winter 1994/95. Although the ice area in winter 1998/99 was larger than the average over the whole study period, the winter total ice volume was smaller than the average. The interannual variation in ice volume was greater than that in ice area, the winter of maximum ice volume was not the winter of maximum ice area.

Figure 3 shows the fluctuation of daily 'spatial mean ice concentration', defined as the ratio between total ice area and total ice extent. The average of ice concentration of the whole Sea of Okhotsk during this period was 81%. The mean ice concentration in the Okhotsk Sea was more than 80% during January–April; however, in every December the mean ice concentration was less than 80% because in the early winter most ice cover consists of ice expanding offshore and the ratio between the marginal ice zone, in which ice concentration always shows low value, and the internal ice covered area is high. In winters which show less ice areas, such as the winters of 1995/96 and 1996/97, the spatial mean ice concentration was under 80% except at the end of January and in all of March. Conversely, in winters when the ice area was large, such as the winter of 1997/98, the spatial mean ice concentration is high, up to 90%. In summary,

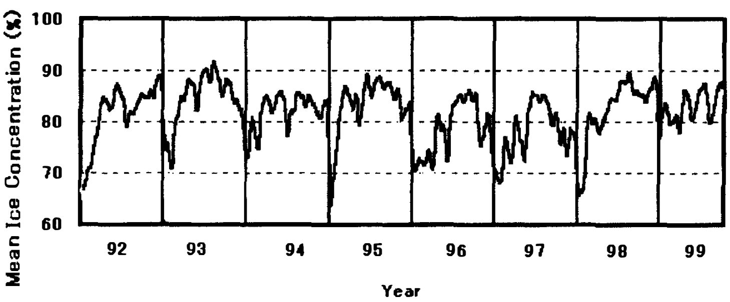

Fig. 3. The 7-day running mean daily spatial mean ice concentration during winters (December–April) for 1992–1999.

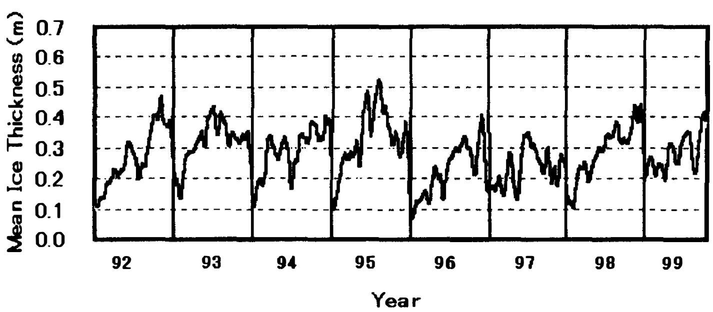

Fig. 4. The 7-day running mean daily spatial mean ice thickness during winters (December–April) for 1992–1999.

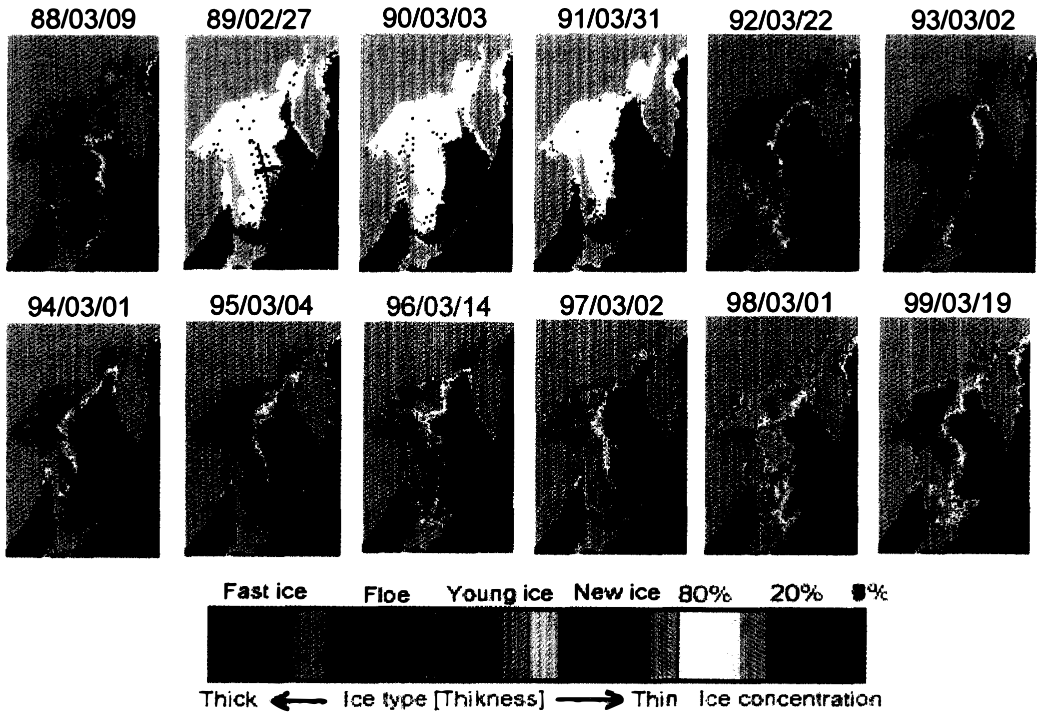

Fig. 5. The ice map for the day of the winter maximum during 1988–1999 winters.

the spatial mean ice concentration is low (high) when ice area is small (large).

The spatial mean ice thickness was calculated by dividing the daily total ice volume by the daily total ice area for the whole Okhotsk Sea, as shown in Fig. 4. The average thickness in the whole Okhotsk Sea during this period was 0.3 m; the yearly maximum thickness appeared in the winter of 1994/95. In the winters of 1995/96 and 1996/97 the ice volumes were small because the mean ice thicknesses were thin, below 0.3 m, except during a few days. In contrast, the other years showed above 0.4 m in thickness in March, when the maximum ice extent appeared. Large ice volumes appeared in the winters of 1992/93, 1994/95 and 1997/98, which showed thick mean ice thickness; on the other hand, the ice volume in the winter of 1998/99, which was the 2nd largest in ice area, was not large, because mean ice thickness was thinner, although above 0.3 m.

Figure 5 displays the ice type distributions on the day of the winter maximum during the winters of 1987/88–1998/99. For the three winters 1988/89–1990/91 the ice concentration maps are displayed without ice type classification, because the 85-GHz channel of SSM/I, which is used to determine ice thickness, was not available during this period. Coastal polynyas can be seen off Ul'ya and Magadan, the coast of the northern Okhotsk Sea and off Okha, northeastern Sakhalin; for example, note the polynyas located in the young ice area colored by orange in the winter of 1992/93 in Fig. 5. These maps show large young (<0.35 m) ice areas in the northern part of the Okhotsk Sea on the maximum ice extent days of the winters 1995/96 and 1996/97. The thick ice (≥ 0.35 m), colored by red and deep purple, on the other hand, covered the northern part of the Sea of Okhotsk in large ice volume winters such as the winters of 1992/93 and 1994/95. These results suggest that the major contribution to the decrease in the yearly ice volume is that ice is thinner on average in the northern part of the Okhotsk Sea because the air is not cold enough to grow young up to first-year ice.

4. The effects of meteorological conditions on yearly ice production

We described the fluctuations of ice area, concentration, thickness and volume in Section 3. In this section we will discuss the effects of meteorological conditions on yearly ice production.

A 'Cold Air Mass Index' (CAMI) is defined as the accumulated daily average of air temperature at 700 hPa height from December through April to investigate atmospheric effects on the ice in this study. CAMI is calculated by accumulating the absolute values of negative air temperatures, which are below -15°C. From meteorological observations in northern Sakhalin taken by the Sea Ice Research Laboratory, Hokkaido University, and Kitami Institute of Technology, the relation between air temperature below -10°C at 1000 hPa height and ice area showed a negative correlation. This result implies that ice area decreases even if air temperature is below 0°C and colder temperature, below -10°C, is needed for expansion of the ice area. Kimura and Wakatsuchi (1999) described the relationship between the ice edge and 10-day running mean data of 2 m air temperature as being that the ice edge continues to advance when the air temperature is colder than -15°C. On the other hand, temperature near the sea surface at 1000 hPa or 2 m height will be greatly affected by the sea ice. Hence the CAMI, which used air temperature below -15°C at 700 hPa height to remove the effect of surface cooling by sea ice from daily air temperature fluctuations, was established due to high response on the sea ice variation in this study.

Figure 6 shows the inter-winter variations of the CAMI, (I) in the northwest Okhotsk Sea (centered at 57.0°N 142.5°E), (II) off the east coast of Sakhalin (52.0°N 147.5°E), (III) in northeastern Hokkaido (57.0°N 142.5°E) and (IV) off the northeast coast of Kamchatka (57.5°N 167.5°E). The time series of the CAMI in the northwest Okhotsk Sea (I) and off the east coast of Sakhalin (II) showed the correlations 0.48 and 0.47, respectively, with total winter ice volume. These areas indicate a good correlation with winters of large ice volume, but correlation with winters of small ice volume was not obvious. In northeastern Hokkaido (III), the correlation was poor or even negative (-0.09). The highest positive correlation (0.81) was seen off the northeast coast of Kamchatka (IV), where air temperature is affected greatly by the Aleutian low.

Figure 7 shows winter (December–April) mean Sea Level Pressure (SLP) for winters 1991/92–1998/99 and indicates that the Aleutian low was strong (weak) in winter when ice volume in the Sea of Okhotsk was small (large). Low pressure below 1003 hPa covered the Kamchatka Peninsula in small ice volume winters, such as 1996 and 1997, because the Aleutian low was strong. In 1999, although the ice area was the 2nd largest, ice volume was smaller because the 1003 hPa isobar passed over the Kamchatka peninsula. The ice volume decreases when air temperature in eastern Kamchatka is higher due to westward warm air advection from the Bering Sea or north Pacific and increases when air temperature in eastern Kamchatka is lower due to northeasterly cold air advection. In the Sea of Okhotsk the wind direction changes as well, and shows the direction from northwest when ice cover is large. The wind

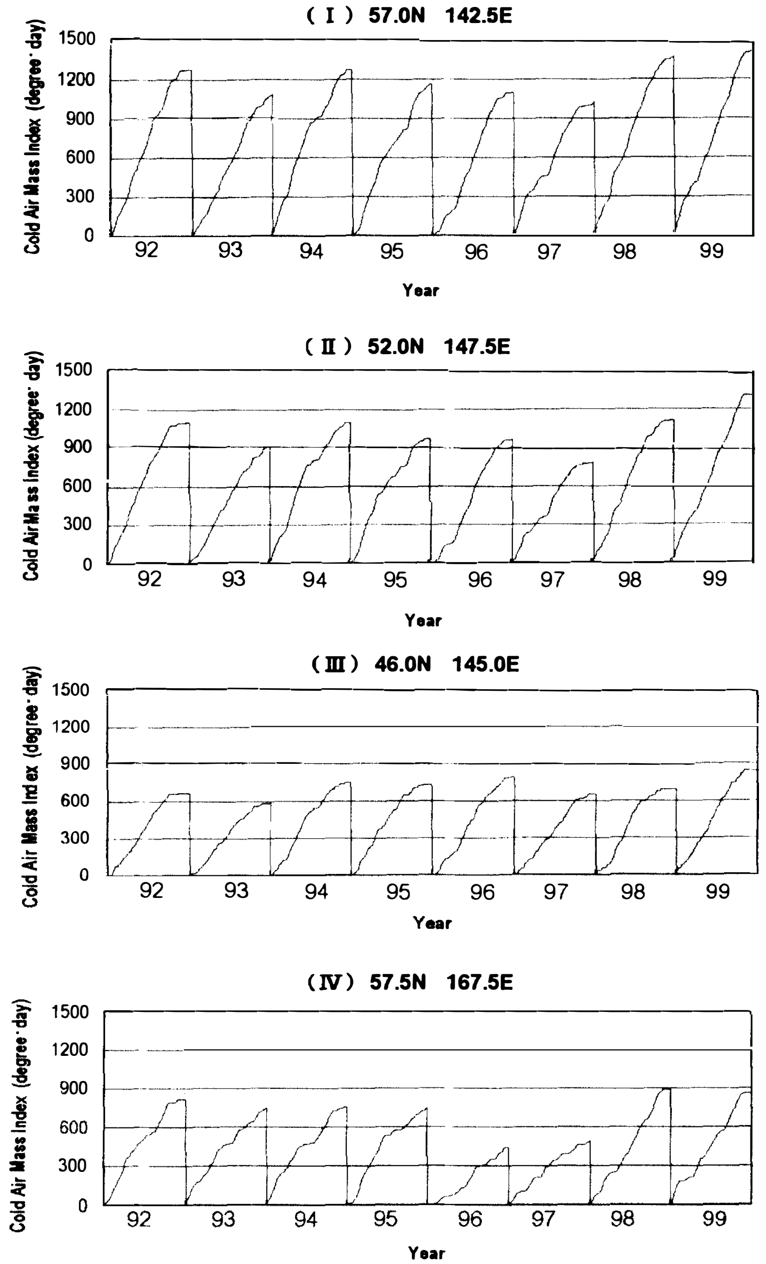

Fig. 6. The Cold Air Mass Index during winters (December–April) for 1992–1999.

direction is southward in low ice volume winters. The wind from the northwest direction contributes to extension of the ice cover toward the east, so that off the coast, hence the coastal polynyas are developed and ice production in the polynyas also is strengthened. SLP also showed lower pressure anomalies around Hokkaido and Sakhalin islands in winters of small ice volume. Winter storms from the south caused these anomalies and melted sea ice away. In other words the 1012 hPa isobar passes over Hokkaido and Sakhalin islands when winter storms frequently pass over the Okhotsk Sea.

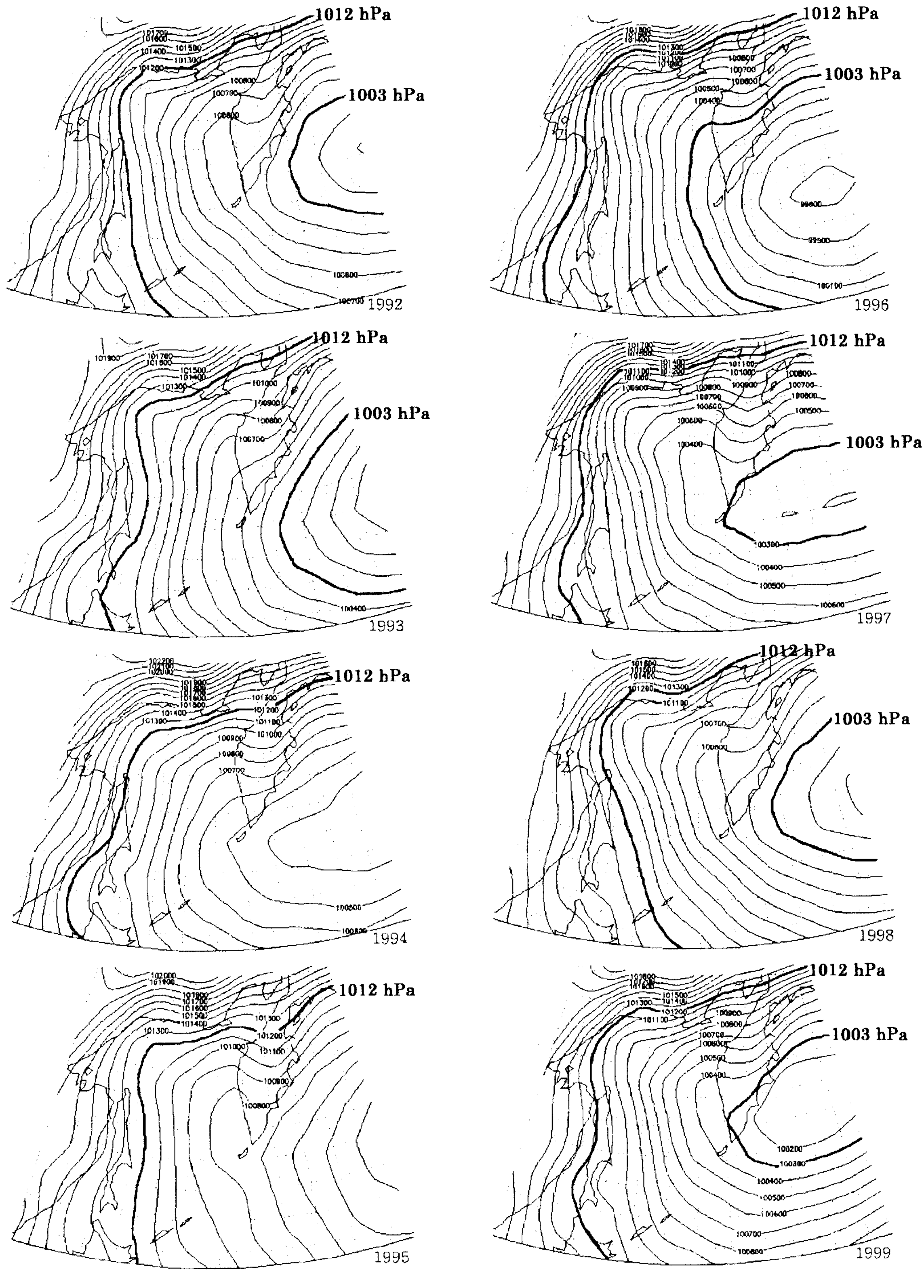

Fig. 7. Winter (December–April) mean sea level pressure for 1992–1999. Contour interval is 1 hPa. Bold contours mean 1012 hPa and 1003 hPa.

5. Conclusions

This paper used the S/KIT algorithm to estimate ice thickness and volume in the Sea of Okhotsk. The averages of ice area, volume, thickness and concentration were 0.60×10^6 km^2, 1.9×10^2 km^3, 0.3 m, 81%, respectively, in this period. The results show that, in the winters of 1995/96 and 1996/97, not only ice areas but also ice volumes were small. Furthermore, mean ice thickness was thin. Large ice volumes appeared in the winters of 1992/93, 1994/95 and 1997/98. Although the 2nd largest ice area appeared in 1998/99, the ice volume was smaller than average in that winter. These results suggest that the yearly ice volume fluctuation is greatly affected by ice thickness in the northern part of the Okhotsk Sea.

By comparing ice volume with the Cold Air Mass Index (CAMI) at 700 hPa height, which is the absolute value of accumulated daily mean air temperatures below -15°C from December through April, the CAMI along the east coast of Kamchatka, where air temperature is related to the Aleutian low strength, indicates the highest positive correlation with ice volume around the Sea of Okhotsk. Winter mean sea level pressure (SLP) shows that the Aleutian low moves westward when ice volume is small and eastward when ice volume is large. Hence the Sea of Okhotsk is covered with higher pressure anomalies, and sea ice extending off the coast is encouraged because of the southeastward wind and the downward cold air advection by the Aleutian low. In other words ice thickness in the northern Okhotsk Sea was thinner and winter total ice volume was smaller, when the 1003 hPa line of winter average SLP passed over the Kamchatka Peninsula, such as in 1995/96, 1996/97 and 1998/99.

Acknowledgments

We used SSM/I data obtained from the National Snow and Ice Data Center (NSIDC). For meteorological data we used NCEP/NCAR reanalysis data via the World Wide Web. Surface air temperature in northern Sakhalin was derived from Sea Ice Research Laboratory, Hokkaido University. This study was partly supported by NASDA through the International Arctic Research Center/NASDA Information System (INIS) research project.

References

Cavalieri, D.J. (1994): A microwave technique for mapping thin ice. J. Geophys. Res., **99**, 12561-12572.

Enomoto, H. (1996): Observation of thin ice area in the Okhotsk Sea and impacts for climatological study. J. Remote Sensing Soc. Jpn., **16** (2), 14-25.

Kimura N. and Wakatsuchi, M. (1999): Processes controlling the advance and retreat of sea ice in the Sea of Okhotsk. J. Geophys. Res., **104**, 11137-11150.

Tateyama, K. and Enomoto, H. (2000): Observation of sea ice thickness fluctuation in the seasonal ice covered area during 1992-1999 winters. to be published in Ann. Glaciol.

Tateyama, K., Enomoto, H., Takahashi, S., Shirasaki, K., Hyakutake, K. and Nishio, F. (2000): New passive microwave remote sensing technique for sea ice in the Sea of Okhotsk using 85-GHz channel of DMSP SSM/I. Bull. Glaciol. Res., **17**, 23-30.

Wensnahan, M., Maykut, G.A., Grenfell, T.C. and Winebrenner, D.P. (1993): Passive microwave remote sensing of thin sea ice using principal component analysis. J. Geophys. Res., **98**, 12453-12468.

(Received March 3, 2000; Revised manuscript accepted August 21, 2000)