Sea-ice motion in the Okhotsk Sea derived by microwave sensors

H. Enomoto[1,2], T. Kumano[1], N. Kimura[3], K. Tateyama[4], K. Shirasawa[4] and S. Uratsuka[5]

[1]Department of Civil Engineering, Kitami Institute of Technology, Kitami, Hokkaido, Japan,
[2]Frontier Observational Research System for Global Change, Yokohama, Kanagawa, Japan,
[3]Earth Observation Research Center, NASDA, Tokyo, Japan,
[4]Institute of Low Temperature Science, Hokkaido University, Sapporo, Hokkaido, Japan,
[5]Comunucation Research Laboratory, Mitaka, Tokyo, Japan

ABSTRACT Sea ice motion in the Okhotsk Sea was analyzed by using satellite microwave sensors and coastal radar. A passive microwave radiometer indicates large-scale ice drift patterns. A dominant ice flow pattern was apparent along the eastern coast of Sakhalin and approaching Hokkaido. Although passive microwave analysis was not available for the coastal zone, SAR data pairs at 12-hour intervals show sea ice deformation patterns near the coast. A series of coastal radar images indicates high frequency variations of ice motion near the shore. These microwave sensors can track the drifting ice which is approaching Hokkaido.

KEYWORDS: Sea-ice; Ice drift; Okhotsk; Remote sensing; Satellite; Microwave; Radar.

INTRODUCTION

Ice drift data are important for monitoring ice conditions in the sea at high latitudes. Drifting ice transports low saline water and cold temperature to the south. When an accident happens in a sea ice field, ice drift is very important information to predict the area of spreading contamination (Emery *et al*, 1997a). Drifting buoys were operated by the Sea Ice Research Laboratory of Hokkaido Univ. to observe ice transport along Sakhalin (Mochizuki *et al*, 1995). They observed an along shore drifting pattern offshore of the northern half of Sakhalin; however, variable drifting patterns were reported off southern Sakhalin and near the ice edge zone in the southern Okhotsk Sea. The oceanic current along Sakhalin has been little known. Recently, some buoy operations have been carried out in this area. The mean surface water movement was investigated recently (Ohshima *et al*, 2002) and a strong current along Sakhalin Island was reported.

This study analyzed sea ice motion in the Okhotsk Sea, by using satellite microwave sensors and coastal radar. Microwave sensors have all weather capability and do not require sunlight, thus they are very useful for observing sea ice. Although SSM/I observation has a coarse resolution (12.5km and 25km), it is useful for observing large-scale features of ice motion on a hemispheric scale at a daily intervals (Agnew *et al*., 1997; Emery *et al*, 1997b). SAR data provide information on fine structures of the ice and ice motion (Kwok *et al*, 1998). Observations by coastal sea ice radar provide continuous information on ice motion. Many studies have been done using the sea ice radar (Ishida, 1975). Satellite data and coastal radar data have large differences in their spatial resolution; thus, few comparisons have been done. However, rescnt development of SAR began to provide detailed image same as coastal radar imagery. This study compares the ice motion data by satellite sensors and radar observation, and discusses capability of these observations. One advantage of coastal radar is the continuity of the observations. This study used a quick repeating cycles of SAR observation within 12 hrs and compares its results with successive coastal radar images.

DATA AND METHOD

This study compares the sea-ice motion data derived by SSM/I, SAR and sea ice radar of Sea Ice Research Laboratory at Mombetsu and discusses their capabilities and limits. Fig.1 shows a map of the observation area in the Sea of Okhotsk.

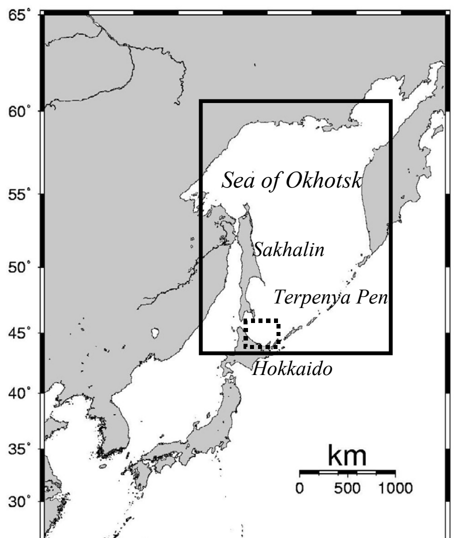


Fig. 1 Observation area in the Sea of Okhotsk. SSM/I (solid square), SAR and sea ice radar data (dotted square) were available in this study.

This study uses RADARSAT SAR data on 24 and 25 Feb., 1998 (dawn-dusk mode: 12-hour intervals), SSM/I (1-day intervals) on the same dates, and a series of sea-ice radar images at 3-hour intervals. Table 1 summarizes the data used in this study.

Table 1. Sea ice data used in this study

Sensor	Area	Spatial res.	Corr. Window	Interval
SSM/I	Sea of Okhotsk	12.5km	75km	day
SAR	Off Mombetsu	20m	5km	12hrs
Sea ice radar	Hokkaido coast	10m~	few km	3hr

The maximum correlation method was applied to satellite and coastal radar data to calculate ice velocity. Many ice tracking observations use a maximum correlation method for a pair of satellite images. Since this method uses a correlation window, the spatial resolution decreases. The spatial resolution becomes 6 to 10 times smaller compared to the original resolution. This limits information obtained in the marginal zone and coastal zone. As the maximum correlation method may produce the average ice motion of the window, sub-window scale motions are smoothed out. This causes some discrepancies with real ice motion or buoy. Tracking of a prominent feature retains the original resolution, but requires high spatial and temporal resolution data.

LARGE SCALE MOTION

For the large scale ice motion, sea-ice motions derived by the SSM/I are available. Mean ice motion over 100km scale is observable from SSM/I 85GHz data. These data are very useful because of the observation interval (1 day) and all weather capability. Fig. 2 shows the ice motion between 24 and 25 February 1998. The red colored area indicates a mean ice speed of less than 10cm/s; the yellow area indicates 10 to 20 cm/s. The green lines are sea level isobars adopted as an indication of the wind field. Ice motions are well correlated with the geostrophic wind field (Kimura and Wakatsuchi, 2000).

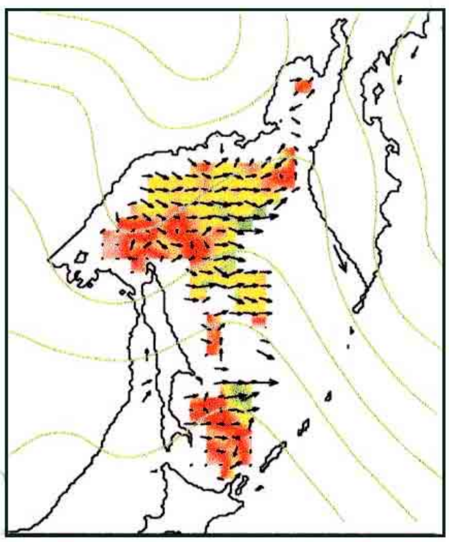


Fig. 2 Sea ice drift obtained from SSM/I imagery (24-25 Feb., 1998). Red: 0-10 cm/s, yellow: 10-20cm/s. Line: sea level pressure.

Although small-scale features were not obtained due to coarse spatial resolution (12.5x12.5km), the mean ice motion over 100km scale is observable from SSM/I 85GHz data. By averaging long-term ice drift data in the Sea of Okhotsk, a dominant flow pattern of sea ice was apparent along the eastern coast of Sakhalin and approaching Hokkaido. Fig. 3 was derived from the mean ice motion vector field for 1992-2001 winter months (December to April). Ice streamlines were drawn to start from 100km interval grid points to fit the vector field. This figure indicates mean the ice drift pattern in the Sea of Okhotsk. The ice drift pattern was concentrated and stable along the Sakhalin coast.

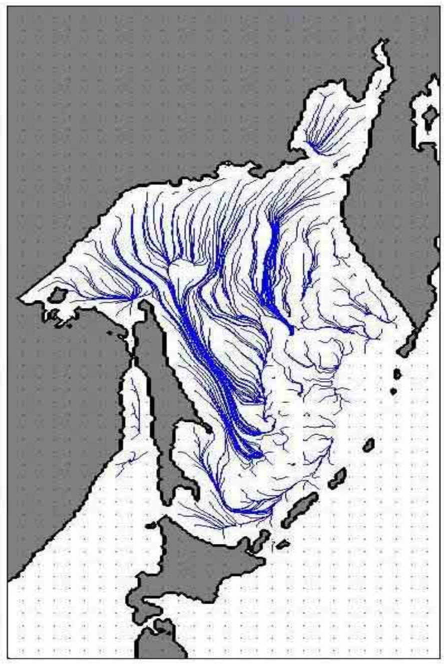


Fig. 3 Mean Ice drift pattern indicated by streamlines in the Sea of Okhotsk. Mean pattern of nine winters, 1992/93-2000/01 is indicated. Each streamline started from a grid point at 100km intervals (indicated as dots).

To validate the satellite ice motion data, buoy data have been used as a reference (Mochizuki *et al*, 1995). The ice motion with high temporal variability is not indicated since averaging long-term data smoothed the ice motion out. The spatial ice drift pattern is also smoothed out since the correlation window is 75kmx75km. There is a blank area of streamlines northeast of Sakhalin Island. This area is known to have frequent polynyas (Alfultis and Martin, 1987). The streamline indicates a lack of steady ice drift around this region. There were few observations of ice motion along a outer edge of the sea ice area. Stable ice flow patterns were not apparent in this area.

Although path of drifting ice was concentrated along the eastern coast of Sakhalin, it became variable when the southward ice flow separated from the Terpeniya Peninsula in the middle part of Sakhalin Island. Predictability of sea ice drift was difficult south of this area, and the ice drift pattern became complex near Hokkaido.

COASTAL ICE MOTION

This study uses the synthetic aperture radar (SAR) data of RADARSAT. SAR data pairs at 12-hour intervals show sea ice deformation patterns near Hokkaido, Japan. Fig. 4 shows an image pair of RADARSAT SAR. The date of observation was the same as SSM/I observation, but the interval is 12hrs.

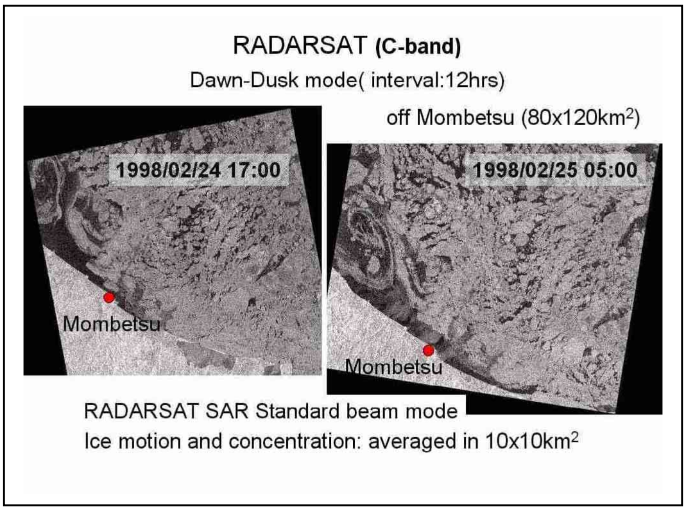


Fig. 4 RADARSAT SAR image pair observing coastal sea ice zone near Mombetsu, Hokkaido, Japan. Dawn-dusk mode data (12hr interval) were used for this study.

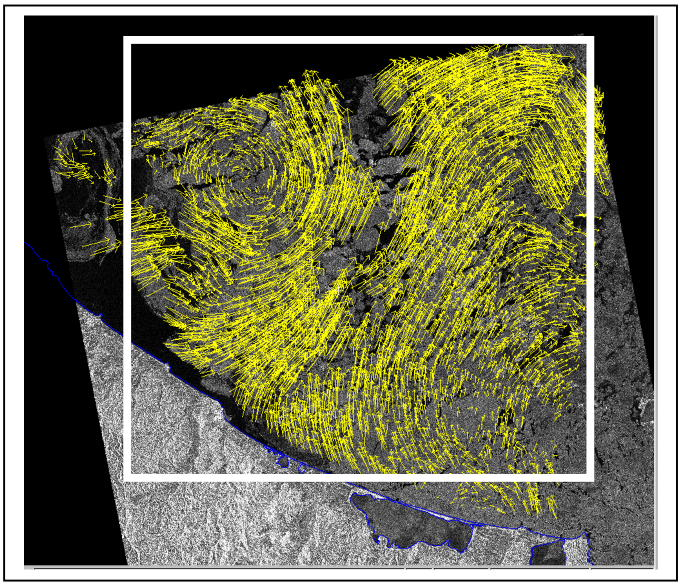


Fig. 5 Ice drift vectors obtained from RADARSAT SAT image pair, off Mombetsu, 24-25 Feb. 1998. The analyzed area for Figs. 6, 7 and 8 is indicated by the square.

Fig. 5 shows the ice vectors obtained from an image pairs in Fig. 4. There are two alternate eddies near the shore. The ice deformation field is indicated as the deformation of cells of 5km set in the sea ice field (Fig. 6). Sea ice motion in the coastal zone is dynamic, and variation of the kinematical field can be seen. Since the sea ice along the Hokkaido coast has many open leads, the ice edge shows high variability and quick deformation.

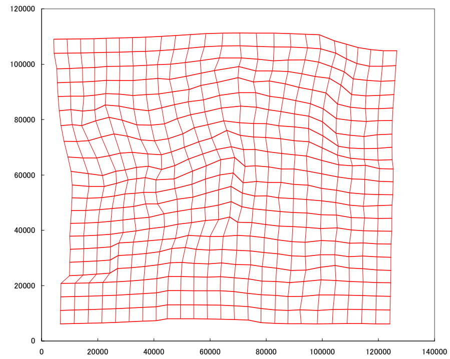


Fig.6 Deformation of sea ice field. Each cell has 5km size.

Fig. 7(a) shows the ice velocity field. The active area can be observed left side of the observation area corresponding to the moving sea ice eddy along the coast. The right side of the image is relatively quiet as the ice concentration is high and ice floes are compacted along the coast.

Divergence, rotation and deformation can be indicated in this figure. These components were obtained as,

divergence $\quad du/dx + dv/dy \quad$ (1),

rotation $\quad dv/dx + du/dy \quad$ (2),

deformation $\quad dv/dx - du/dy \quad$ (3),

where u and v are ice speed components in the x and y directions. These parameters are indicated in Figs. 7(b)-(d). Eddies are indicated in Fig. 7(c). A shearing field of sea ice was indicated in Fig. 7(d).

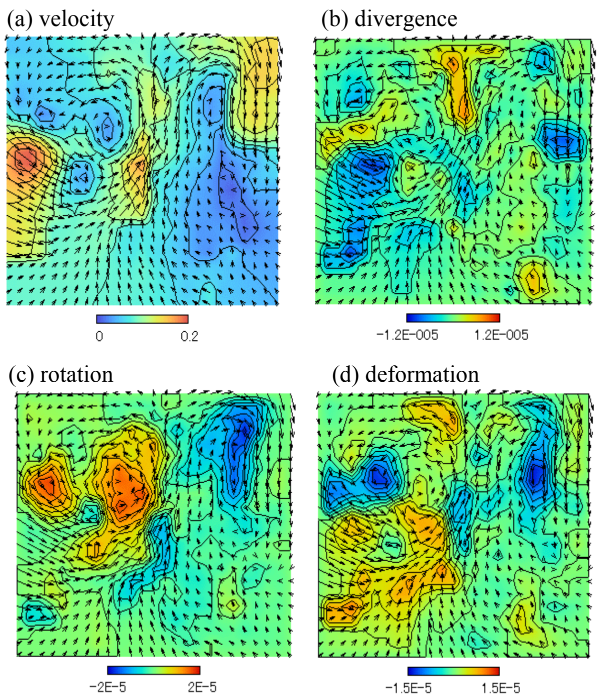
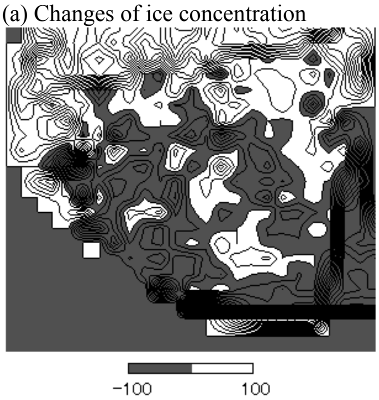


Fig. 7 Velocity, divergence, rotation and deformation of sea ice field. The arrows in all figures indicate ice velocities.

Ice coverage was changed during the 12 hrs, and ice concentration changed in this field. Changes in ice concentration were estimated as difference of the binary images of SAR (Fig. 8(a)). From the ice motion vector and ice concentration of the former SAR image, ice area advection was calculated (Fig. 8(b)). The change in ice concentration can be explained by the ice area advection, since ice melting and freezing seem to be small in this observation interval.

(a) Changes of ice concentration



(b) ice area advection

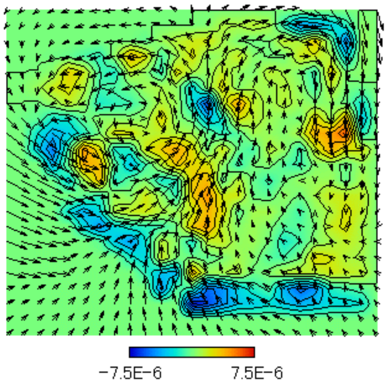


Fig. 8 (a) Changes in ice concentration (%) in 12hrs. (b) Sea ice area advection (km^2/s).

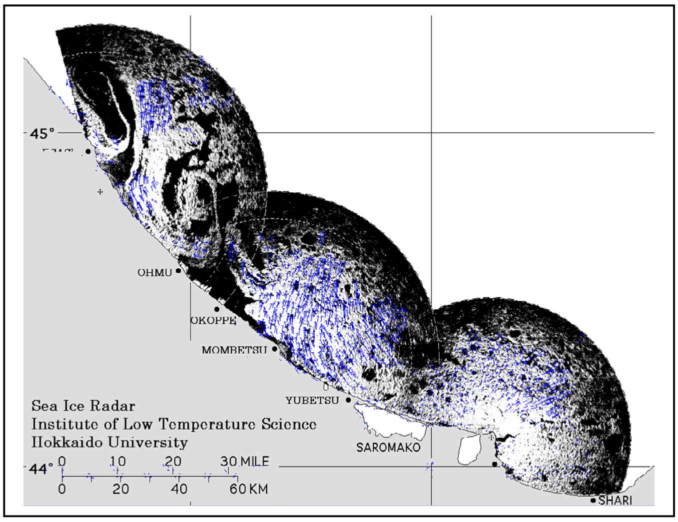


Fig. 9 Ice motion analyzed from sea ice radar for 3hr intervals.

There were differences between the areal differences of sea ice cover by concentration data and by the ice advection analysis. The areas are either small pack ice area or low concentration areas near open water. In these areas, ice can converge and rafting and ridging can occur; thus, information on ice deformation is needed.

Coastal radar data indicate high frequency variations of ice motion. Ice motion vectors were obtained for the first 3-hrs period of the SAR observation interval (Fig. 9). Sea ice radars were operated along the Hokkaido coast by the Sea Ice Research Laboratory of Hokkaido University and their coverage focuses the coastal zone.

DISCUSSION

SAR and sea ice radar analyses indicate complex patterns of sea ice motion along the shore of Hokkaido. SAR imagery provides detailed ice motion. This study, additionally, attempted to investigate the temporal variability of ice drift in the SAR data interval. Successive radar images can indicate temporal variations of ice movement at shorter intervals than, which satellite data cannot observe. A series of sea-ice radar images with 3-hour interval was analyzed for this purpose. Three sea ice radars are operated along the Hokkaido coast by the Sea Ice Research Laboratory of Hokkaido University. Coastal radar data indicate high frequency variations of ice motion. Ice motion vectors were obtained for every 3hrs (Fig. 10). Sea ice drift changed its direction even in 3hr intervals; consequently their directions were rotated clockwise. SAR analysis showed the averaged features which the coastal sea ice radar showed to 3hrs interval in 12 hrs.

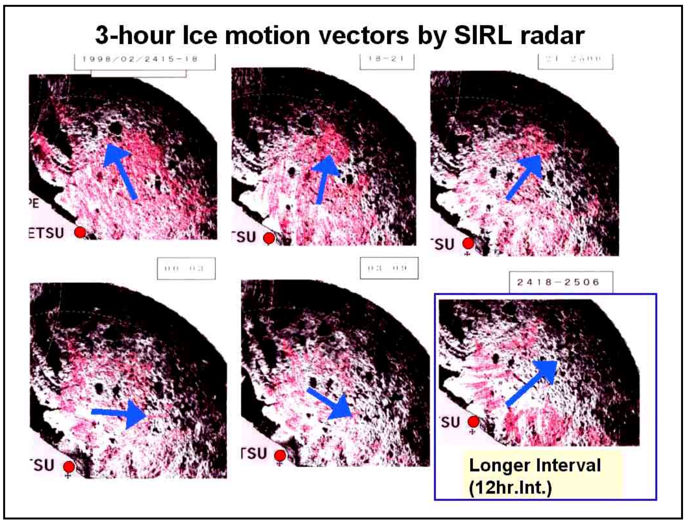


Fig. 10 Ice motion derived from successive radar images at 3hr intervals. Blue arrows indicate mean direction. Image of longer interval (12hr) was obtained from the image pair of the first and last observations.

On the other hand, passive microwave radiometer (SSM/I) data of DMSP satellite DMSP indicate the large-scale ice drift patterns in the sea of Okhotsk and dominant southward flow pattern to Hokkaido. Ice drift is an important information concerning traffic accidents in the sea ice area. Based on the results of this study, the southward drifting along the Sakhalin is dominant in the Sea of Okhotsk and its behavior is rather stable.

However, all of southern Sakhalin Island, the ice drifting pattern has highly variable features; therefore, prediction of ice drift might be difficult. Oceanic mesoscale eddies will greatly affect the ice drifting pattern in this region. Thus, monitoring the oceanic eddies is a important work for sea ice change in this area. This study used SSM/I data; however, the spatial resolution is not ideal for maximum correlation analysis for features less than 100km in diameter. A new microwave radiometer AMSR has become available recently. The spatial resolution will be improved. The observation interval will be improved to twice a day. This better performance of microwave radiometer data will improve observation data in the complex ice field. Applications of PIV (Particle Image Velocimetry) techniques will be available for tracking characteristic features in the sea ice field (Haniu *et al*, 2002). It will not reduce the spatial resolution, thus more detailed motion will be monitored.

For the observation of large-scale ice motion, ice motion analysis by SSM/I data is useful, but for observation of ice in the coastal zone the present technique is limited. SAR and coastal radar data are required to observe drifting ice approaching Hokkaido coast.

CONCLUSIONS

This study attempted ice motion analysis using satellite microwave sensors and coastal radar. Passive microwave radiometer SSM/I is useful for large-scale ice motion analysis and SAR describes detailed features of ice motion.

As the large-scale drifting pattern, a dominant ice flow is apparent along the eastern coast of Sakhalin and approaching Hokkaido. The ice drift pattern was concentrated and stable along the Sakhalin coast, but it became variable when the southward ice flow separated from the Terpeniya Peninsula of Sakhalin. For predicting ice drift along Sakhalin Island, the northern half will be easier as there is steady flow. In the southern part, ice monitoring is difficult due to its high spatial and temporal variability. Monitoring mesoscale eddies might be required to predict ice drift.

Approaching Hokkaido and the southern ice edge zone, the ice movement pattern became complicated. This study analyzed ice motion vectors from pairs of SAR images. Dawn-dusk mode SAR data are useful for monitoring detailed ice motion in the active ice zone. Ice kinematics is indicated by separating the divergence, rotation and deformation rate. These parameters can provide useful ice information. Changes of ice concentration can be explained mostly by ice advection, however, freezing, melting and rafting processes should be identified for precise monitoring.

Successive observation of coastal radar has a great advantage for monitoring active ice kinematics, especially along the coast and near the ice edge. However, as coastal radar has a narrow view of observation, combination with passive microwave radiometer, with wide observation view, will be a powerful tool for sea ice monitoring.

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