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SAR STUDY OF THE TRANSITION ZONE BETWEEN FASTICE AND DRIFTING ICE IN THE BOTHNIAN BAY IN MARCH 1997

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ABSTRACT

In this study RADARSAT (ScanSAR and Fine-resolution modes) and ERS-2 SAR images are used to investigate ice motion in the Bothnian Bay during a field experiment where GPS and other in situ ice observations were made. The study is focused on the transition zone between the drifting ice in the central and western part of the Bothnian Bay and the fastice in the northern and eastern part of the bay. It is demonstrated that SAR imagery with 75 m pixel size, combined with 200 – 300 m accurate geolocation, can be used to determine small ice displacement, of order 500 m - 1 km in this transition zone where ridge formation is the most important ice process. Interpolated ice velocity fields can be determined to grid cells of 5 – 10 km or less depending on the requirements from the users. In addition, SAR images can be used to identify shear zones, opening of leads and other discontinuities on the ice velocity field which is usually smeared out when using automatic ice motion algorithms. Detailed ice velocity fields can be used to validate mesoscale ice models which are under development for improved ice forecasting. .

1. INTRODUCTION

Synthesis Aperture Radar (SAR) observations of sea ice from satellites is important in the studies of local ice cover deformation and mesoscale ice dynamics. A number of SAR ice investigations have been carried out in the Baltic Sea in order to understand how SAR images can discriminate between various ice types and ice roughness conditions in the region and be used in ice navigation (i.e. Carlström, 1995; Ulander 1994) This study is focused on one aspect of SAR ice observation, namely to describe ice motion in the transition zone between the fast ice and drifting ice on the Finnish side of the Bothnian Bay. The study was part of the ICE STATE field experiment, ZIP-97, which took place in the Bothnian Bay in March 1997. In addition to SAR data from RADARSAT and ERS-2, GPS drifters, helicopter surveys, airborne laser measurements and ice modelling activities were carried out (Riska et al., 1998). Several algorithms have been published which can automatically estimate ice motion from series of satellite images (i.e. Holt, et al., 1992). In this paper we use a correlation method (Sandven et al., 1991) combined with analysis of ship track and drifting buoy data to identify shear zones and convergence zones between the fastice and the drifting ice.

2. ACQUISITION AND PROCESSING OF SAR DATA

During the period from 22 February to 18 March, a total of 9 SAR images (or stripes) were available from the ERS-2 and RADARSAT satellites in near real-time. After processing at NERSC in near real-time, most of the SAR images were transferred digitally to the ZIP-97 Headquarters on Hailuoto Island for use in planning of the field investigations. ZIP-97 offered the first opportunity to study sea ice in the Baltic Sea with both ERS and RADARSAT images as well as optical satellite images, aerial photographs, laser profilometer, etc. (Haapala and Lepparanta, 1997). From RADARSAT, three different modes of images have been obtained: ScanSAR Narrow Mode (SN1), Fine Resolution Mode (F3) and Extended High Incidence angle Mode (H3). These different modes have incidence angles varying from 20° to 55° and resolution down to 8 m for one-look.

Both ERS-2 and RADARSAT SAR data were downlinked and pre-processed to full-resolution images at Tromsø Satellite Station (TSS). The images which were distributed via internet in near real time were spatially averaged to "low" resolution images while full resolution images were delivered on CD-ROM. For RADARSAT SAR data the full resolution images were resampled at TSS, using a reduction factor of 5 or 6 to reduce the file size and the radar speckle noise. The RADARSAT images were obtained in three different modes, as shown in Table 1.

Table 1. Resolution and size of the RADARSAT images

Date 1997	Mode	Pixel size of full resolution image (m)	# columns in full res. image	Image width (m)	Reduction factor to create averaged image	Pixel size of averaged image (m)
10 March	H3	12.50	6 000	75 km	6	75.0
13 March	F3	6.25	8 000	50 km	5	31.25
17 March	SN1	25.00	12 000	300 km	5	125.0

Absolute calibration is not yet known accurately for RADARSAT images, which makes it unfeasible to compare pixel values between ERS and RADARSAT data. In this study we have focused on the extraction of ice features for determination of ice motion which does not require absolute calibration of the SAR data.

3. DESCRIPTION OF SEA ICE DYNAMIC CONDITIONS

The winter of 1996 - 1997 was milder than an average winter with ice covering the Bothnian Bay and parts of the Bothina Sea in the middle of February when the ice had its maximum extent (Haapala and Lepparanta, 1997). The ice in the Hailuoto area started to develop quickly in December including buildup of ridges. In late January the whole Bothian Bay was icecovered, but opened up again due to heavy winds and mild weather. In February and March, alternating periods of warmer and colder weather, and corresponding southerly or northerly winds, dominated. The fastice as well as ridges were built up gradually in the eastern part of the Bothnian Bay.

3.1 General description of RADARSAT ScanSAR image

The ScanSAR Narrow mode image of 17. March was the first wideswath SAR image covering practically the whole Bothnian Bay (Figure 1). The image shows the following main features:

"A" represents several stages of fastice along the northern and eastern sides of the Bothian Bay, shown as relatively dark areas. The fastice consists of large areas of level ice and various amounts of surface roughness, shown by different grey tones, and individual ridges shown as bright line features. Area denoted "A1" (Fig. 1) is thin level ice which has been formed in the last 2 -3 days in the lead created as the main icepack drifted southwards. Area "A2" is older and thicker fast ice which started to develop in December containing ridges which are grounded many places. The thickness of this ice was around 70 cm. Area "A3" is a zone which earlier in the winter ice had ice moving in response to variable wind forcing, but was fastice in March. This zone has more ridges and rubble ice than "A1" and "A2". The thickness of level ice varied between 50 and 90 cm, while the maximum thickness observed in a ridge was 7 m.

"B" is the transition zone between fast ice and drifting ice further west. The SAR image shows more bright features in this zone compared to the fast ice. These features are caused by numerous ridges and rubble fields. This is the area where GPS drifters were deployed in ZIP-97 (shown by the white circle in Fig. 1). The drifters showed very small ice motion in northeasterly direction east of 24° E, while they indicated southward motion west of 24° E.

"D" marks the drifting ice in the western part of the Bothnian Bay, which started to move southwards immediately after the onset of northerly winds in the period from 13 to 15 March. The drifting packice field is diverging, creating leads between clusters of floes or congested ice areas which move like a solid body. The leads were refrozen and became covered by thin level ice which appears dark in the SAR image. The air temperature in this period varied between - 6° and -12°C. "W" indicates areas of predominantly open water and scattered new ice in the western part of the Bothnian Bay and Bothnian Sea.

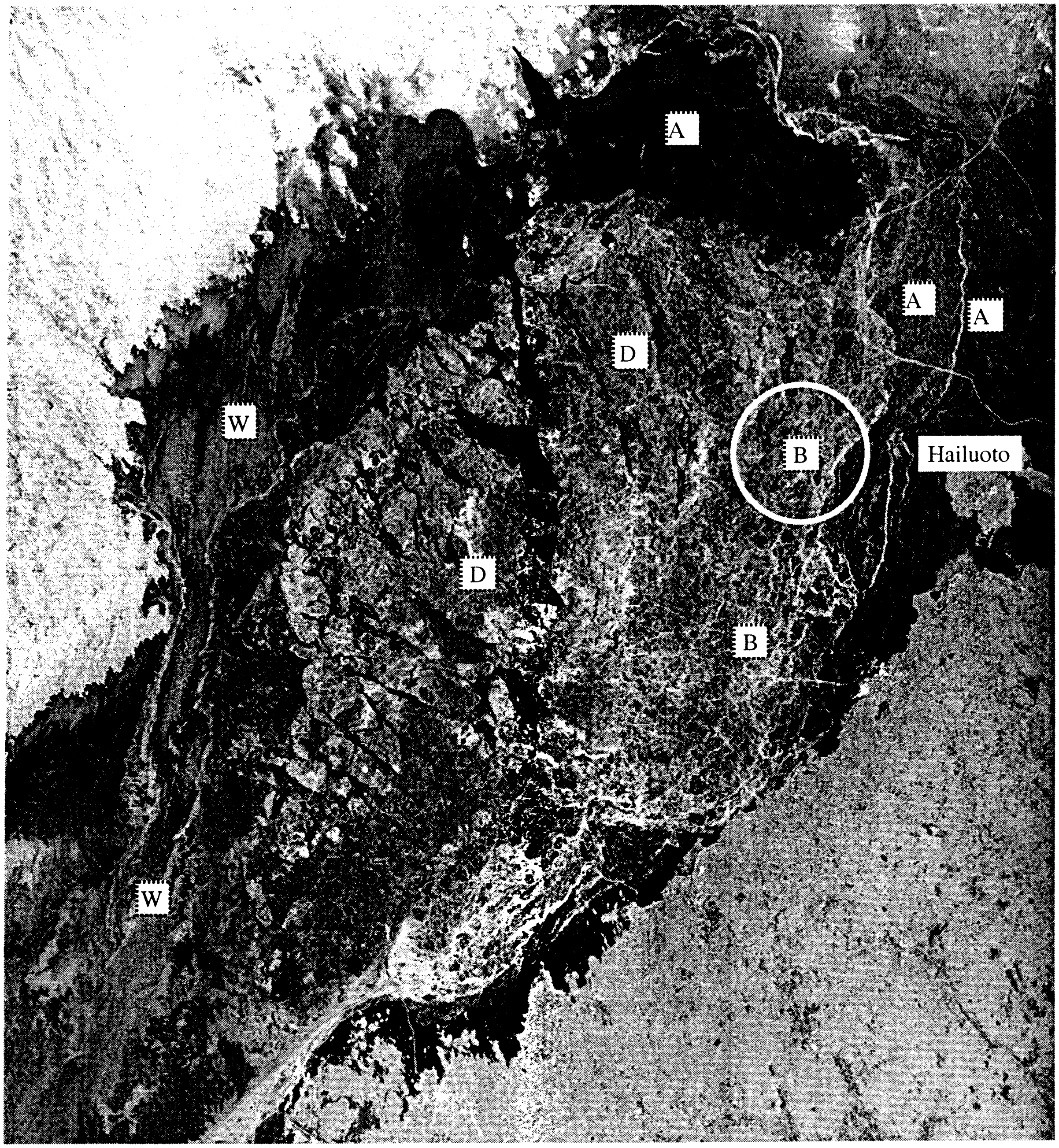

Figure 1. The first RADARSAT ScanSAR (SN1 mode) image of the sea ice in the Bothian Bay was obtained on 17 March 1997. The pixel size is averaged to 125 by 125 m from the original 25 m. The resolution of the printed image is between 500 m and 1 km. The white circle indicates the area where ice motion was investigated by GPS drifter during ZIP-97.

3.2 Observation of shear zones

The image of the area west of Hailuoto (Fig. 2) shows the fastice zones "A2" and "A3" as well as the transition zones to the drifting ice; "B", "C" and "D". The pixel size is 125 m in this sub-image, which similar to the pixel size in Fig. 1. Due to zooming of a smaller area it is possible to see more details about ridges, floes, leads and icebreaker canals compared to the overview image in Fig. 1. All features in the right part of the image remained stationary throughout the experiment period. For example the lead denoted "L1" did not change its size or shape. Some large individual ridges ("R") were observed in the first SAR images obtained a month earlier and persisted throughout the ice season.

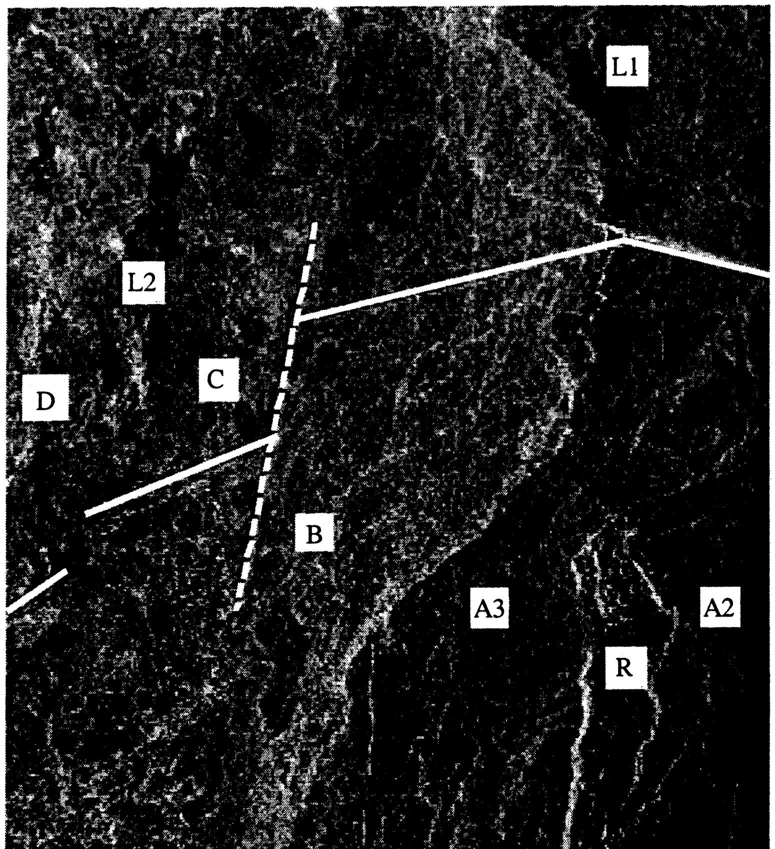

Figure 2. Subimage of the RADARSAT ScanSAR image of 17. March 1997. The subimage covers about 40 by 40 km just west of Hailuoto, in the transition between fast ice and drifting ice. © Canadian Space Agency/Agence spatiale canadienne 1997.

The superimposed straight white lines enhance the icebreaker canals in the ice cover which appear as bright, thin, almost straight lines. The displacement of the white lines shows how the ice pack in the left part of the image has moved in the previous two days. A SAR image of the same are taken on 15 March showed this icebreaker canal as a straight line. The discontinuity of the icebreaker canal marks the shear zone between the ice area "B" which represents the transition between fast ice and drifting ice areas "C" and "D". Note that the two drifting ice masses ("C" and "D") move southwards with different speed and experience a slight linear shear in the velocity field. The shear zone between "C" and "D" creates several open leads ("L2"), which were not observed two days earlier. The shear zone between "B" and "C", on the other hand, (indicated by the dashed white line) does not create any lead even if the velocity shear is larger. The displacement of area "C" is about 7 km in two days, which corresponds to a mean velocity of 0.04 ms^{-1}.

3.3 Ice velocity fields

To obtain synoptic estimates of the ice velocity over the whole Bothnian Bay it is necessary to obtain repeated SAR images which cover the drifting ice repeatedly every 1 – 3 days. During the ZIP-97 experiment we were able to collect SAR data over a period of about 10 days with SAR coverage every 2 - 3 days. In the first period, from 10 to 13 March when the most intensive acquisition of SAR data from RADARSAT and ERS-2 took place, the winds were south-southwesterly, pressing the ice in a northeasterly direction. From 13 to 15 March the wind turned northeasterly and started to push the drifting ice in a southerly direction. The fast ice along the northern and eastern coasts of the Bothnian Bay remained motionless. From 15 to 19 March the drifting ice continued to move southwards, causing the lead in the northern Bothnian Bay to widen.

The most critical factor in determination of the drift vectors was to recognize sufficient number of features to build up a fine-meshed gridded velocity field and to estimate the displacement at small velocities (<0.01 ms^{-1}) found in the transition zone between fastice and drifting ice. This transition zone was investigated from 10 to 13 March when the drifting ice moved towards the fastice in the area west of Hailuoto. (Fig. 3).

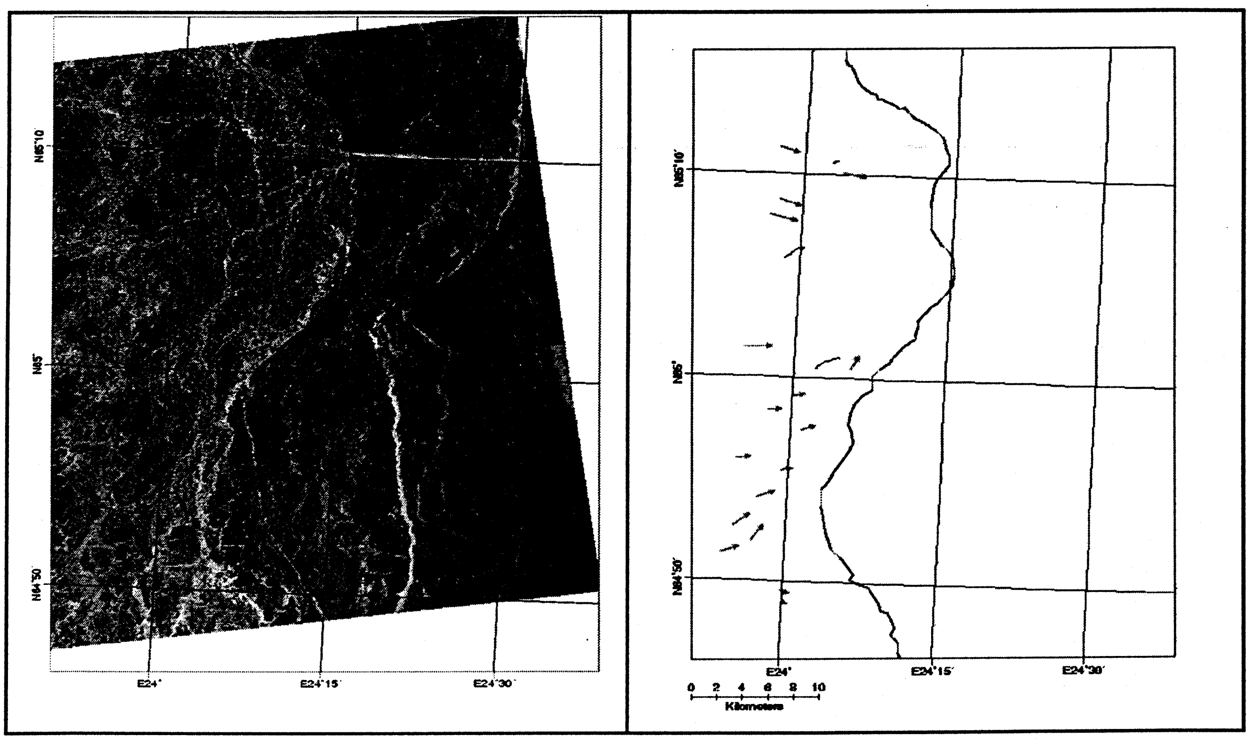

Figure 3. a) Subset of the RADARSAT Fine-resolution image of 13 March just west of Hailuoto. b) Ice drift vectors from SAR images (arrows) and drifting buoys (short lines without arrow) in the transition zone to the fastice. The major ridge running in north-south direction (marked by the long line) was stationary.

With Fine resolution SAR images, using a pixel size of 75 m, it was possible to identify small displacements in the ice field, down to a few hundred meters over a three-day period. Geolocation of the images was determined by assuming that the predominant ridge features in the fastice was stationary. The accuracy of this geolocation is 3 – 4 pixels (i.e. 200 – 300 m). The drift vectors show a typical displacement of 2 km over 3 days, corresponding to a mean speed of 0.008 ms^{-1}. The drift vectors also show that there is convergence in the ice field in a 3 - 5 km wide zone west of the stationary ridge. The drift turns northwards between 64°50'N and 65° N, while it has a southerly component around 65° 10'N. There is considerable local variability in the drift vectors within 10 by 10 km grid cells, suggesting that models for simulation of mesoscale ice drift should have a resolution of at least 5 by 5 km in this region. The formation of ridges in the convergence zone was documented by in situ observations during the field experiment.

From 13 to 15 March the packice started to move southwards due to the onset of northerly winds. A displacement of ice features of up to 14 km was found in the central part of the Bothnian Bay, corresponding to a mean velocity of 0.08 ms^{-1}. From 15 to 17 and 19 March the northerly wind speed increased from less than 5 ms^{-1} to about 10 ms^{-1}, increasing the ice drift speed in southerly direction (Fig. 4).

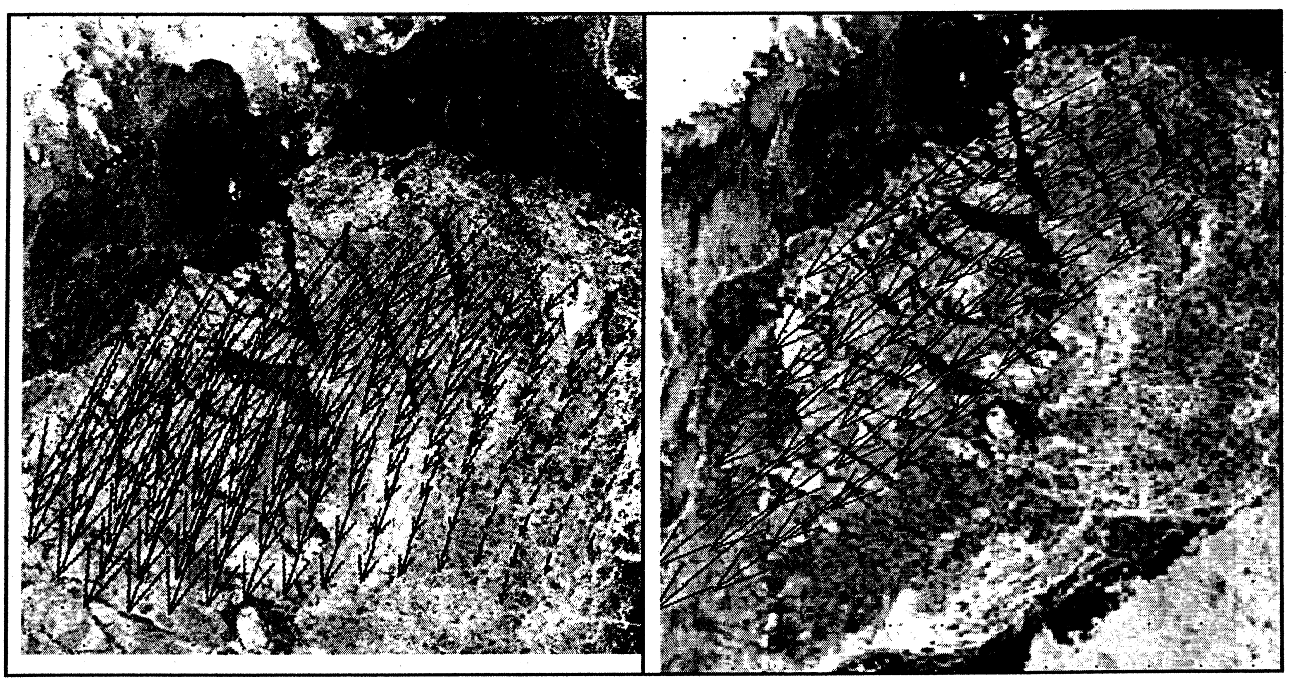

Figure 4. a) Gridded mean ice velocity field in the period 15 - 17 March 1997, derived from ERS-2 and RADARSAT images, superimposed on the SAR image from 17 March. One of the GPS drifters (white arrow) was included in the interpolation of the velocity field. b) Mean ice velocity field in the period 17 - 19 March, derived from two RADARSAT ScanSAR images, and superimposed on the image from 17 March. The grid cell size is 10 km.

Maximum ice displacement observed in this period was 40 km in the western part of the Bay, corresponding to a mean ice velocity of about 20 cms^{-1}. The interpolated velocity field, shown in Fig. 4 a, is based on a selection of drift vectors from the area covered by two consecutive SAR images and one from the GPS drifters. A uniform grid surface was fitted to the data (nonuniformly-spaced) and a triangle-based linear interpolation was used. The velocity field is interpolated to a grid size of 6 km. The interpolated drift vectors smeared out real discontinuities in the ice motion which can take place when a lead opens up or a shear zone occur as observed in Fig. 2. Such discontinuities are not resolved by a gridded ice velocity field.

The last period for which ice motion was estimated was from 17 to 19 March, when two RADARSAT ScanSAR images were used to calculate ice drift over the whole Bothnian Bay (Figure 4 b). The northerly wind speed increased to 15 ms^{-1}, causing the ice displacement to be up to 45 km in the southwestern part and about 25 km in the northern part (Fig. 4 b), which represent a mean velocity ranging from 0.24 to 0.14 m s^{-1}. This caused a stretching of the ice field shown by the increased size of the leads.

It is noteworthy that there is a strong velocity field in the western side of the bay and apparently a sharp transition to the stationary ice in the eastern side. In Fig. 4 b no interpolation has been performed between the drifting ice and the stationary ice, as was done in Fig. 4 a. Since we have shown that there can be discontinuous transition between the fast ice and the drifting ice (Fig. 2), it is likely that the velocity field in Fig. 4 b, with a sharp transition between the two ice regimes, is more realistic than the smoothed transition demonstrated in Fig. 4 a.

3.4 Comparison with GPS drifters

An array of five GPS drifters were deployed in the transition zone between fastice and drifting ice west of Hailuoto during the ZIP-97 experiment (Haapala and Lepparanta, 1997). The positions of the drifters have been extracted for the same periods as SAR ice displacement were estimated: 10 - 13, 13 - 15, 15 - 17 and 17 - 19 March. The movement of the drifters for these periods are shown in Fig. 5. When the drifters functioned well, they provided reliable estimates of the ice motion, with position accuracy within 200 - 300 m.

From 10 - 13 March all 5 buoys were operating, showing a northeasterly motion in the whole study area. In the period 13 - 15 March, the two western buoys, deployed in the drifting ice (557 and 559) were turning towards south because the wind changed to northerly direction. The three eastern buoys were deployed in ice which was assumed to be stationary. These buoys were all stuck in ice as the ice field converged towards east with associated ridge formations. Two of these buoys stopped data transmission because they were caught in ice. A comparison between SAR derived vectors (not shown) and GPS drifters shows that the drifters had a southeasterly motion while the SAR vectors were oriented towards south. This discrepancy can be explained by the fact that the SAR image was obtained around 1000 GMT on March 13 and did not capture the predominant eastward motion which took place in the beginning of this two-day period.

From 15 to 17 March only buoy no. 557 continued to drift in southward direction, while buoy no. 559 was caught in the fastice. Buoy no. 557 moved about 10 km in two days, which is much less than the maximum displacement found further west from SAR images, showing up to 40 km displacement in the same period. The motion of this buoy slowed down as it approached the fastice where it became stuck one day later.

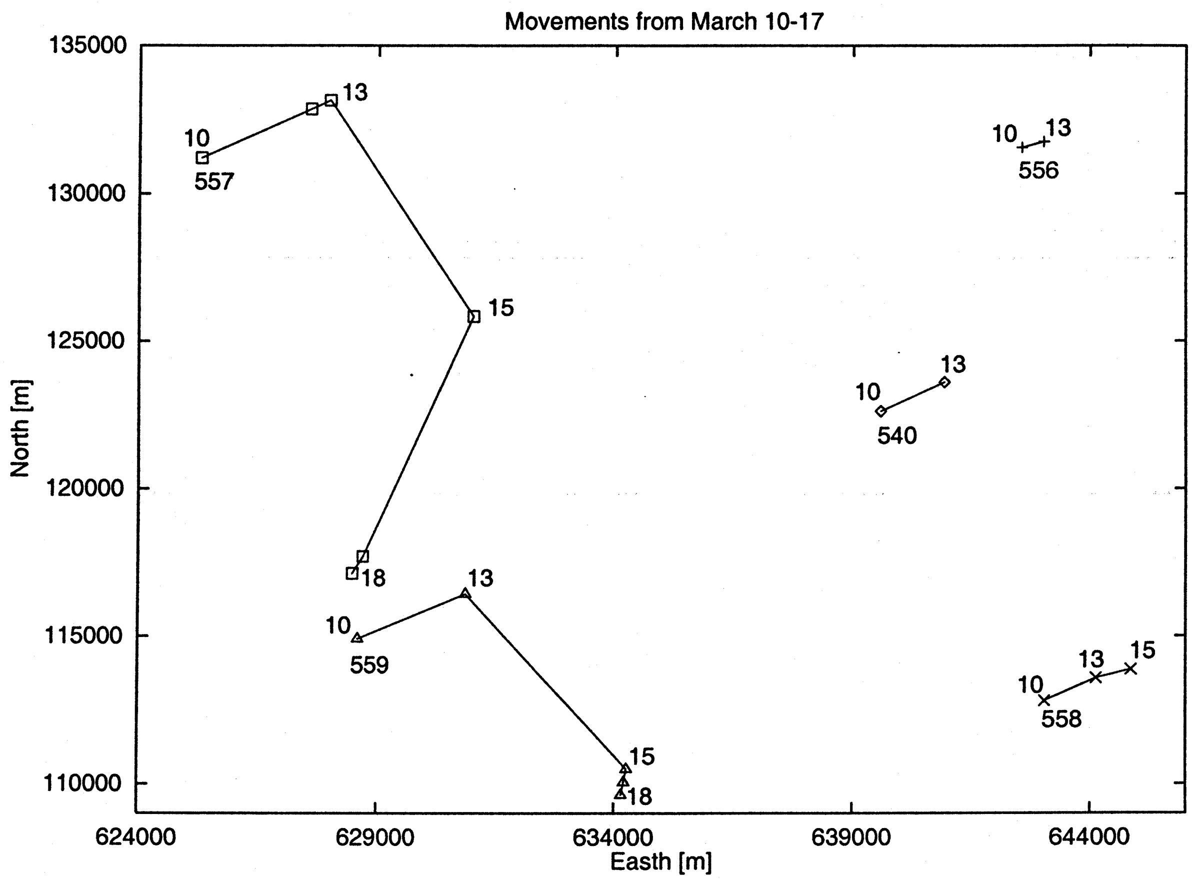

Figure 5. Buoy positions from the GPS drifter plotted with 2 - 3 days interval.

4. RESULTS AND CONCLUSIONS

The study has demonstrated that consecutive SAR images with pixel size of about 100 m, both from ERS and RADARSAT, can be used to estimate ice velocity in the transition zone between fastice and drifting ice in the Bothnian Bay. The velocity fields were interpolated from unevenly spaced drift vectors to gridded vectors in a mesh of size 6 - 10 km. Feature recognition of the ice pack, which is required to determine ice displacement, was

unproblematic for the drifting ice when the displacement was significant (i.e. more than 2 - 3 km) and interpolation to gridded velocity fields is done with a mesh size of 10 km or more. However, for ice displacement of order 1 km or less it was difficult to obtain sufficient number of reliable velocity vectors. The reason is limitation in the image geolocation combined with the difficulty to recognize features in ice of 100 % concentration with many ridged areas. In the transition zone between fastice and drifting ice, it was possible to measure ice drift of less than 0.01 ms^{-1}. Geolocation to an accuracy of 200 – 300 m was achieved by assuming large ridges in the fastice area to be stationary. The SAR derived ice velocities were compared with GPS drifters, showing an overall good agreement between the two methods.

In addition to velocity fields, individual shear zones could also be identified from the SAR images, by studying the displacement of icebreaker canals and the creation of new leads over a 2 - 3 day period. The transition zone between fastice and drifting ice in the area west of Hailuoto could be identified in the SAR image from 17 March as two narrow shear zones. The transition zone could therefore in this case be described as two discontinuities in the ice velocity field rather than a smooth transition from higher to lower velocity across the zone. The existence of such sharp shear zones is important for the local scale ice dynamics. It is difficult to observe such phenomena unless there is a very dense array of drifters or SAR images showing recognizable features which define the shear zones.

The interpolated velocity fields can be used to determine convergence and divergence in the ice pack, which are important parameters for ice navigation because they indicate where the ice pressure is high and low. The velocity fields are prepared for use in the mesoscale ice model, with grid cells of order 5 - 10 km, which is implemented for the Baltic Sea as part of the ICE STATE project. The velocity fields will primarily be used in validation of the model results. A longer term objective is to assimilate SAR derived velocities into mesoscale ice models for improved ice forecasting.

ACKNOWLEDGEMENT

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