551.467
551.326

A CASE STUDY OF PACK ICE DISPLACEMENT AND DEFORMATION FIELD BASED ON LANDSAT IMAGES

by

MATTI LEPPÄRANTA

Institute of Marine Research
Helsinki, Finland

Abstract

A 24-hour change of the ice situation in the Bothnian Bay in April 1979 is analyzed. The ice pack experienced a westward shift of 1–3 km with areal contraction of a few per cent and counterclockwise rotation of about one degree. Largest deformations occurred at the ice edge.

1. *Introduction*

Observations of the drift and deformation of pack ice in the Baltic Sea have been recently made much from drifting ice stations (*e.g.* LEPPÄRANTA, 1981b). From the data the governing processes in pack ice dynamics could have been studied and parametrized. The results have been then applied in numerical modeling of ice drift (*e.g.* LEPPÄRANTA, 1981a). In order to carry out sensitive tests to improve the existing models, synoptic fields of pack ice drift and deformation are very much needed. We shall see below that such fields, in the model scale, can be successfully obtained from LANDSAT images. The method has been earlier used in the Arctic seas (*e.g.*, HIBLER *et al.* 1974, VINJE 1977).

2. *Material and methods*

LANDSAT orbits are repeated with the period of 18 days which is much longer than the time-scale of pack ice motion in the Baltic Sea. However, at the Baltic latitudes there is still a wide overlap in successive image lanes and favourable areas

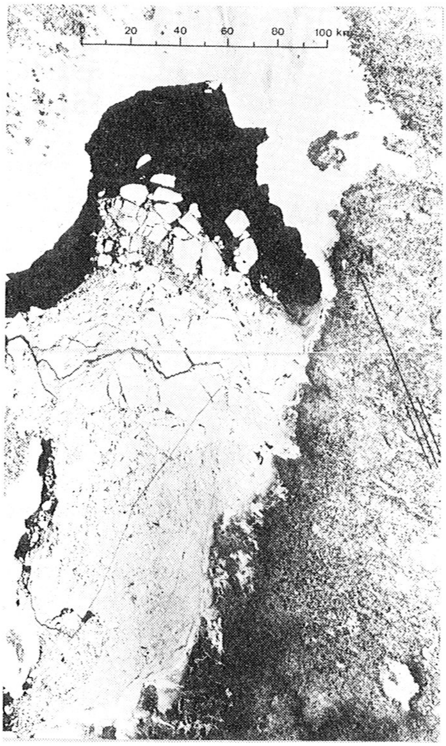

Figure 1a. LANDSAT image over the Bothnian Bay on 17 April 1979, 09.06 GMT.

Figure 1b. LANDSAT image over the Bothnian Bay on 18 April 1979, 09.12 GMT.

are mapped twice with one day interval in each 18-day cycle. The whole Bothnian Bay (the northernmost basin of the Baltic Sea) is such an area.

An excellent pair of images over the Bothnian Bay was obtained on 17 April, 9.06 GMT, and 18 April, 9.12 GMT, in 1979 (Fig. 1). In both cases the sky was clear over the whole basin. In addition, in April ice conditions distinct floes are easily distinguished, and consequently the displacement field in the ice pack can be estimated.

On 17 April a high pressure stretched over the basin and winds were low or moderate blowing mainly from westerly directions. Here we refer to the surface wind (altitude 10 m) estimates for different sea regions provided routinely by the Finnish Meteorological Institute. The main shift direction in the ice pack was west, *i.e.* against the wind, and hence the ice must have been driven by the sea. The daily average of the ice speed was less than 5 cm/s. The routine water level measurements of the Institute of Marine Research, Finland, and SMHI, Sweden, indicated sea surface tilts of $\sim 10^{-7}$ only. This means that neither the gravitational force nor the geostrophic flow induced by the tilt can explain the movement of ice. A current speed of 5–10 cm/s should have been sufficient to overcome the wind stress and give the above net speed to the ice. A few days before the LANDSAT overflight ground truth measurements were made showing that in the central area of the ice pack the mean level ice thickness was 50 cm and the mean equivalent thickness of ridges 20 cm.

The displacement vector $\boldsymbol{u}$ (here two-dimensional) is defined in the material frame of reference as

$$\boldsymbol{u} = \boldsymbol{u}(\boldsymbol{X}) = \boldsymbol{x} - \boldsymbol{X}, \tag{1}$$

where $\boldsymbol{X}$ and $\boldsymbol{x}$ are the positions of a particle in the initial and final configurations, respectively (*e.g.* HUNTER, 1976). In this work the displacement field was estimated through determining the shifts of a number of traceable floes and averaging them to a rectangular grid with the spacing of 15 km. Of interest to our deformation studies is the displacement gradient tensor

$$U_{ij} = \partial u_i / \partial X_j . \tag{2}$$

Here these partial derivatives were estimated through taking the first-order differences in the displacement grid centered for the centers of the grid squares. Following then the infinitesimal deformation theory the strain tensor and rotation can be calculated from their definitions

$$\epsilon_{ij} = \tfrac{1}{2}\,(U_{ij} + U_{ji}), \tag{3}$$

$$\omega = \tfrac{1}{2}\,(U_{21} - U_{12}), \tag{4}$$

respectively. The positive direction of rotation is counterclockwise. The principal strains

$$\epsilon_1, \epsilon_2 = -\tfrac{1}{2}\epsilon_{ii} \pm \sqrt{(\tfrac{1}{2}\epsilon_{ii})^2 - (\epsilon_{11}\epsilon_{22} - \epsilon_{12}^2)}, \tag{5}$$

where $\epsilon_1 \geqslant \epsilon_2$, give the maximum and minimum normal strains; $\epsilon_1 - \epsilon_2$ equals twice the maximum shear strain and $\epsilon_1 + \epsilon_2$ the relative areal extension. The directions of the principal strains equal $\arctan \{Z_2^{(k)}/Z_1^{(k)}\}$, $k = 1, 2$, where $Z^{(k)}$ is a non-trivial solution of the eigenvector equation $(\epsilon_{ij} - \epsilon_k \delta_{ij}) Z_j = 0$ (summation over j; $i = 1, 2$). The directions are necessarily perpendicular to each other.

3. *Results and discussion*

Except for the southeast corner of the basin the displacement field could be estimated and typical values of 1–3 km/day were found (Fig. 2). The mean wind speed was only around 3 m/s. It is very difficult to estimate what would be the pure wind drift for such a weak wind (*cf.* Leppäranta 1981b); the wind factor of 1 % gives about 3 km/day which should be of the correct order of magnitude. Consequently, in the region where the ice drift is opposed to the wind the current speed must be of the order of 5 cm/s. However, here we have neglected the effect of internal friction within the ice which possibly could somewhat increase the

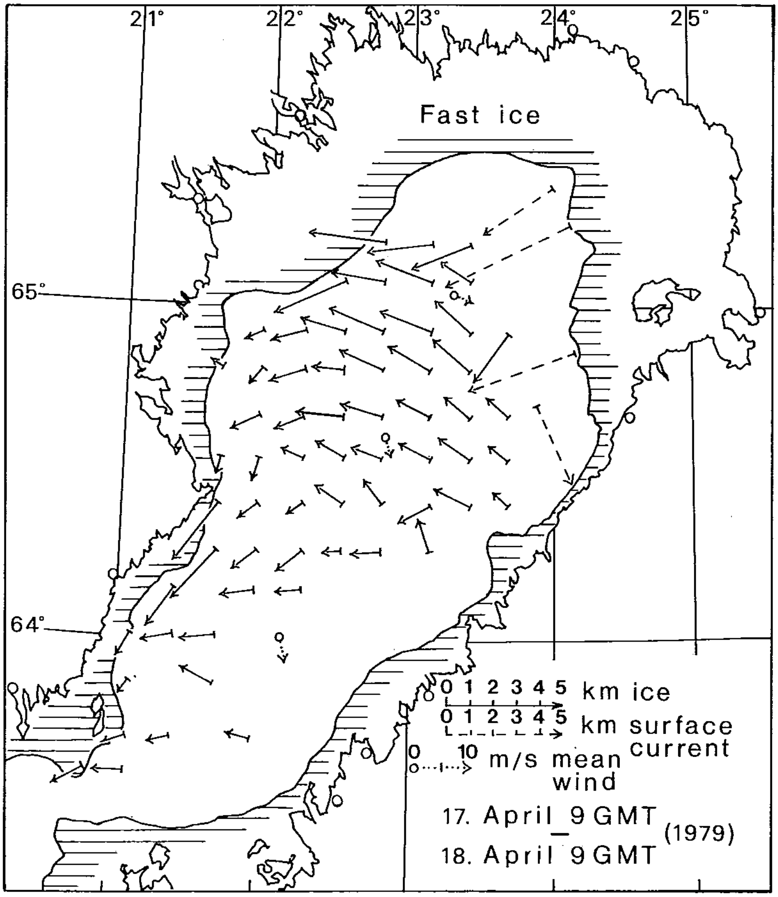

Figure 2. Estimated pack ice displacement field and mean surface wind.

required current speed.

The ice drift pattern reflects a counterclockwise turning from northwest to southwest in the drift direction when crossing the basin from east to west. We can see two vectors opposing the general pattern at the northeast ice edge. This could be due to a topography induced turning of the main current system before the ice edge. At the northeast fast ice edge from 64°50′N north a westward surface current could be seen in enlargements of the LANDSAT images (through the drift of a small amount of new ice).

The principal strain diagram (Fig. 3) shows at the ice edge generally extension

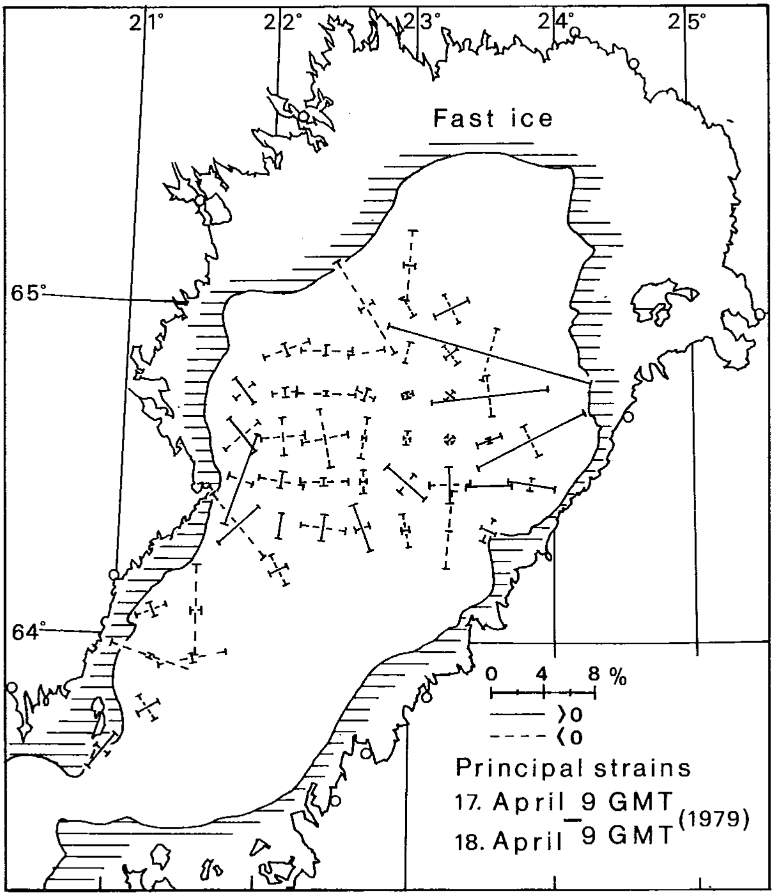

Figure 3. Estimated principal strains in the ice pack.

perpendicular to the edge and contraction in its direction. Deformation is at its largest at the northeast ice edge. In the central part of the western basin there is a large convergent area north of 64°30'N bounded in south by a divergent zone; this is clearly seen in closing and opening of leads in Figure 1. Since the external forces are in our case small the strains reflect only rearrangements in the amount and distribution of leads.

In the region where the deformation field could be estimated the ice pack experienced a total net areal change of a few per cent and a total rotation of about one degree (Figs. 4–6). The radius of rotation (displacement per rotation) was thus

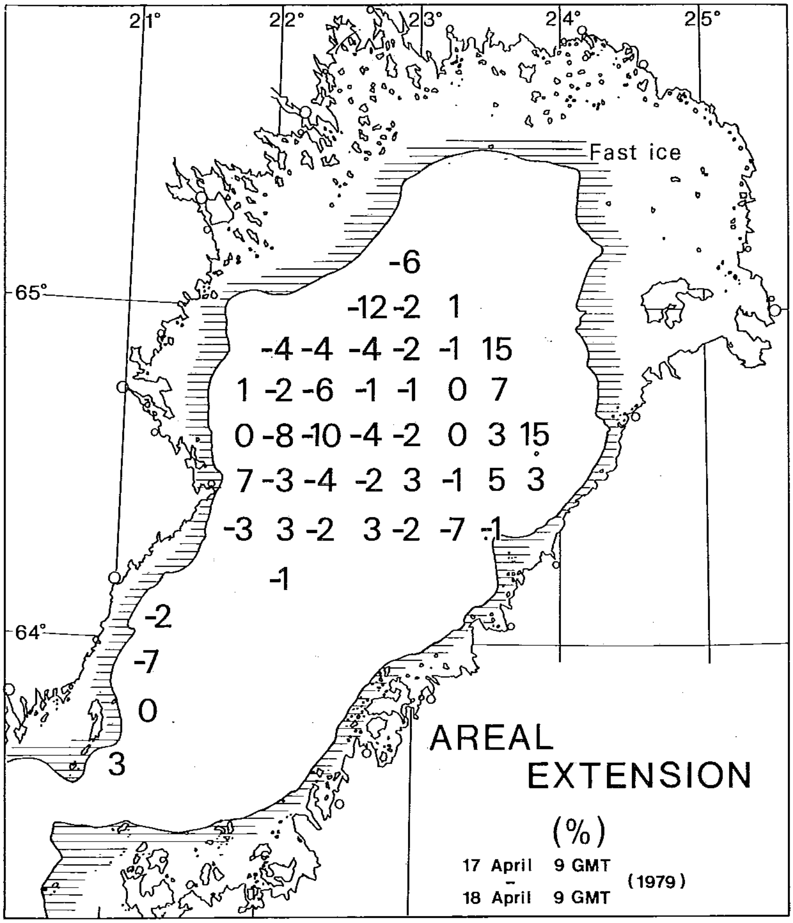

Figure 4. Estimated areal extension in the ice pack.

~100 km which counts to ~2/3 of the region diameter. The line at about 64°20′N, where the rapid extension of the basin width begins, had the strongest shear strain in the interior and varying sign of areal extension. North of the line areal extension was negative except at the northeast ice edge. The whole ice edge experienced stronger shears than the interior and a little south of 65°N two distinct areas with clockwise rotation are seen.

The features in the deformation field in the interior pack seem to be consistent with our field results (*e.g.*, LEPPÄRANTA, 1981b). At the ice edge, a very active zone was found. The edge was not compact but distinct floes could freely respond

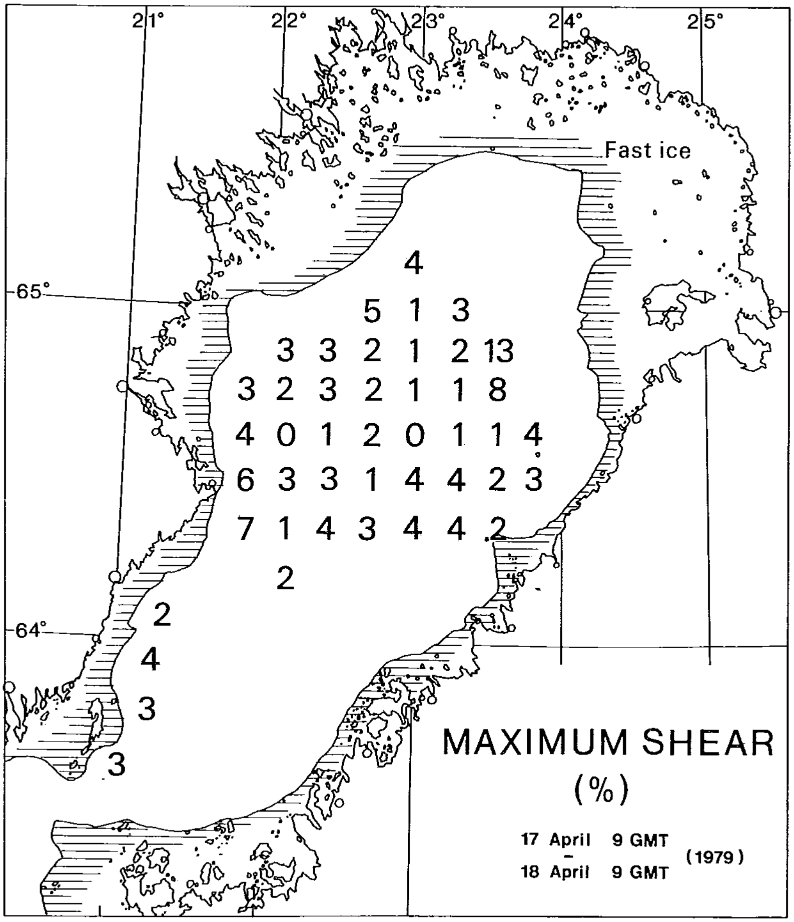

Figure 5. Estimated maximum shear strain in the ice pack.

to the external forces which are much influenced by the surface type change at the edge. In addition, the air temperature was about –10°C giving rise to high instability above the open water area.

Observed synoptic fields of pack ice drift and deformation are very useful in developing ice drift models. Especially, a better insight into the ice rheology is obtained when observed and simulated deformation fields can be compared. Therefore the present study should be repeated for a few more cases of various ice and external conditions. Further more, in cases of low ice compactness the ice inter-

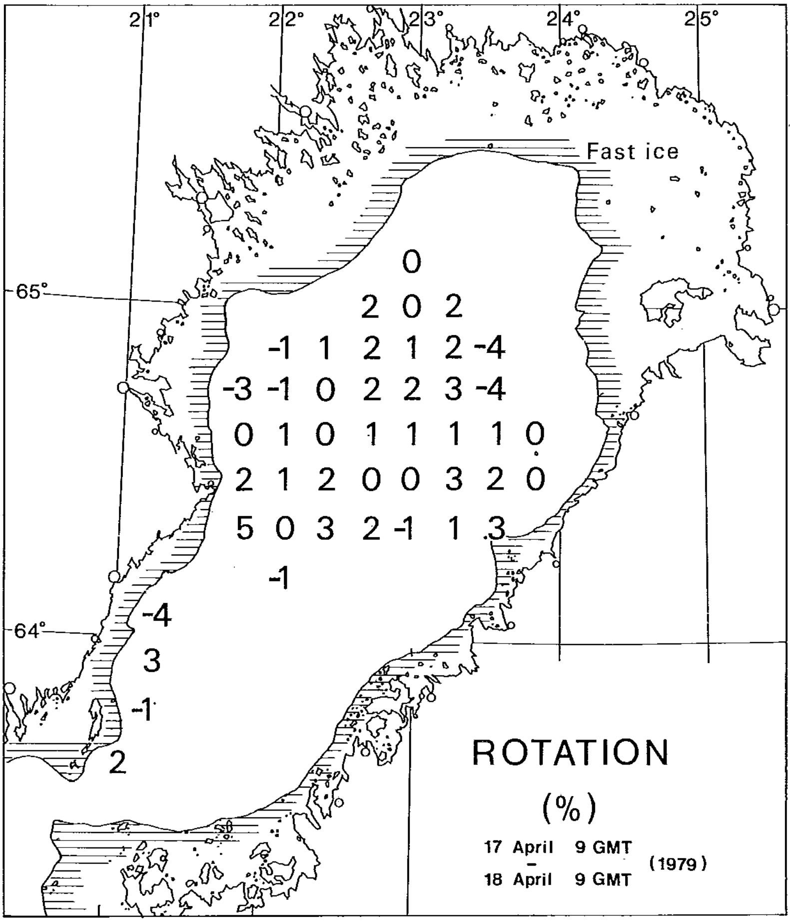

Figure 6. Estimated rotation in the ice pack (1 % = 0.57 deg).

action has not a significant influence on the drift of ice and hence floes can be used to track surface currents.

Acknowledgements: I wish to express my thanks to Mr. Jussi Paavilainen, Geographic Survey of Finland, for his help.

REFERENCES

HIBLER, W.D., III, ACKLEY, S.F., CROWDER, W.K., McKIM, H.L. and D.M. ANDERSON, 1974: Analysis of shear zone ice deformation in the Beaufort Sea using satellite imagery. In: Reed, J.C. and J.E. Sater (eds.), *The Coast and Shelf of the Beaufort Sea,* p. 285–296. The Arctic Institute of North America.

HUNTER, S.C., 1976: *Mechanics of Continuous Media.* Ellis Horwood, England, 567 p.

LEPPÄRANTA, M., 1981a: An ice drift model for the Baltic Sea. *Tellus,* **33**, 583–596.

–»–, 1981b: On the structure and mechanics of pack ice in the Bothnian Bay. *Finnish Mar. Res.* **248**, 3–86.

VINJE, T.E., 1977: Sea ice studies in the Spitsbergen – Greenland area. *Landsat report E77-10206,* U.S. Department of Commerce, National Technical Information Service, 45 p.