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SIZE AND SHAPE OF ICE FLOES IN THE BALTIC SEA IN SPRING

by

MATTI LEPPÄRANTA

Institute of Marine Research
Helsinki, Finland

Abstract

Aerial photographs taken at two instants of time (one month interval) in the Bothnian Bay are used to study geometric properties of ice floes in the melting season. The floe size distribution is considered to be best described in terms of the areal coverage. The data shows a big change: floes with characteristic diameter larger than 1 km disintegrated and the relative area of the small floe group (diameter < 0.1 km) increased by the factor 3. The form of ice floes, described with elongation and shape factor, is found to be in the statistical sense invariant in the time and size domain. Generally floes can be considered elliptic with the average elongation of 1.7.

1. *Introduction*

In spring the ice melts away in the Baltic Sea. Ice floes become rotten and hence break easily which transfers probability mass from large to small floes in the size distribution. However, it is not known quantitatively how the floe size distribution changes. An additional open question is that what happens to the form of ice floes during the melting period. These phenomena are thought to have important physical implications (*e.g.*, WADHAMS *et al.*, 1981). First, lateral ablation of ice should increase when floes get smaller and, second, ice rheology is probably affected by floe characteristics.

This work is purely descriptive presenting geometric properties of ice floes during the melting period in the Bothnian Bay in 1982 (the northernmost basin of the Baltic Sea). It is based on aerial photography at two instants of time (one month time interval), each covering a sea area of about 720 km^2. Only the horizontal characteristics are considered; ice thickness variations are out of the scope of this paper.

2. *Material and methods*

In spring 1982 lines of aerial photographs were taken twice in the Bothnian Bay, on 21 April and 19 May (Fig. 1). At the time of the first case the melting period had just begun and by mid-June all the ice disappeared. Ice conditions were normal in the spring 1982. In april ice thickness was 40–70 cm and in mid-May 20–50 cm.

For both cases two lines of about 60 km length and 6 km width were photographed; thus the covered surface area is 360 km^2 per line. Each line consists of eleven pictures with a small overlap on consecutive ones, and each picture covers a 6 x 6 km^2 area. Examples are shown in Figs. 2a–b. For the analysis the photographs were enlarged so that the scale became 1:25 000. First the pictures were manually analyzed. The major and minor diameters l_1 and l_2, respectively, and the surface area A were estimated for the floes with $l_1 \geqslant l_{10} = 0.1$ km (4 mm in the pictures); l_1 and l_2 were taken as the sides of the smallest rectangle which covers the floe and A was obtained with a planimeter. In addition, for each picture the total surface areas of open water, small floes ($l_1 < l_{10}$) and large floes ($l_1 \geqslant l_{10}$) were integrated with a planimeter.

Two-dimensional geometric properties are commonly described with the characteristic diameter, elongation and shape factor defined as

$$l = \sqrt{l_1 \cdot l_2}, \tag{1}$$

$$e = l_1/l_2, \tag{2}$$

$$\kappa = A/l^2, \tag{3}$$

respectively (*e.g.*, Harr, 1977). By definition $l_2 \leqslant l \leqslant l_1$, $e \geqslant 1$ and $\kappa \leqslant 1$. For a rectangle, ellipse and isosceles triangle κ is 1, $\pi/4$ and 1/2, respectively. The above quantities were statistically analyzed from the ice floe data and all the pictures of the same day were then combined together. The cutoff diameter for l was put to $l_0 = 0.1$ km as above for l_1; the floes with $l < l_0$ were added in the group of small floes.

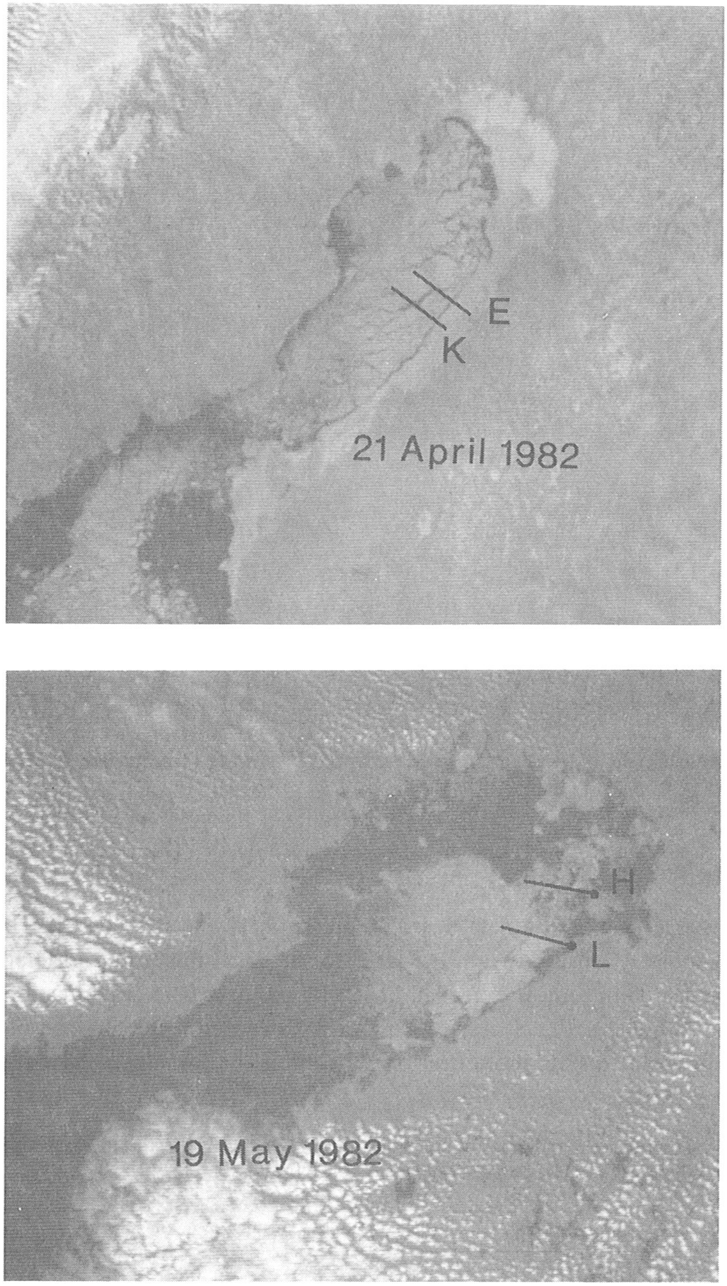

Fig. 1. The lines of aerial photographs shown on NOAA–7 images over the Bothnian Bay.

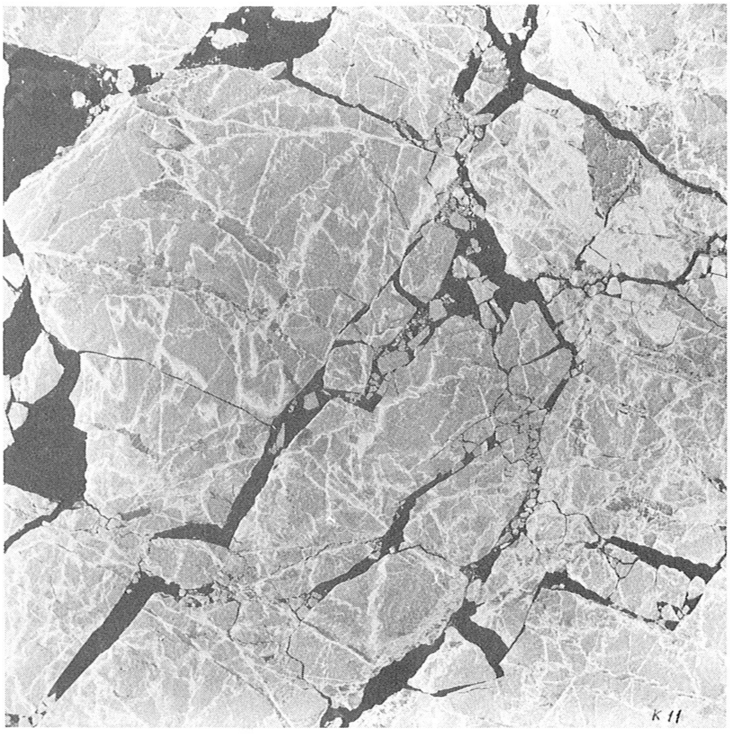

Fig. 2a. An example of aerial photographs on April 21: number 11 in the line K. (Side length 6 km.)

3. *Results*

The average ice compactness was 0.84 on April 21 and 0.69 on May 19 and there was a clear transition from the large to the small floe group (Table 1). In both cases ice compactness exceeded in several pictures 0.95 which can be taken as a lower bound for the closest packing of floes (note: in the absence of freezing). It is not possible to state more because we cannot resolve very small openings from the pictures.

Table 1. Ice compactness and areas of small and large floes relative to the total ice area (the floe group boundary at characteristic diameter = 0.1 km).

Case	Ice compactness	Small floes	Large floes
April 21	0.84	0.18	0.82
May 19	0.69	0.71	0.29

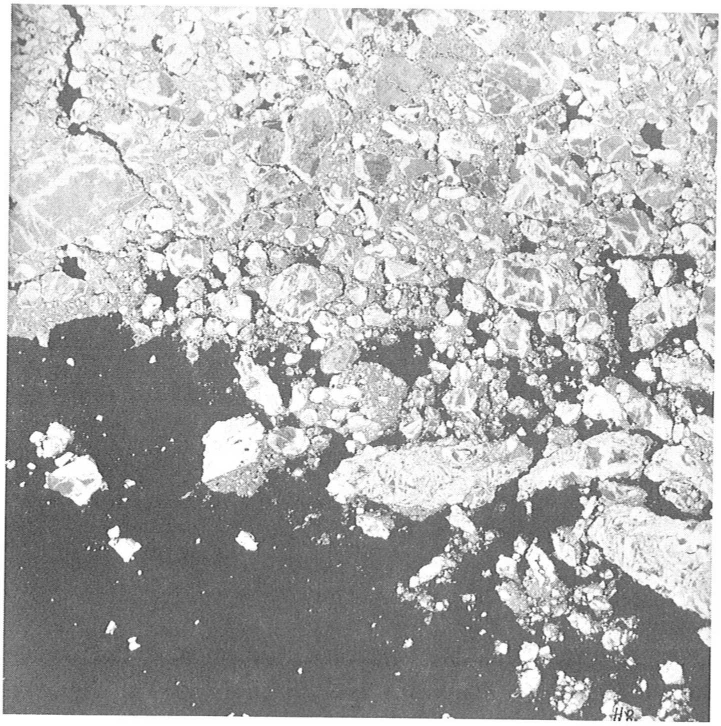

Fig. 2b. An example of aerial photographs on May 19: number 8 in the line H. (Side length 6 km.)

In both cases the number of analyzed floes was about fifteen hundred (Table 2). The mean and standard deviation of the characteristic floe diameter dropped heavily during 21 April – 19 May but those of the elongation and shape factor remained practically constants. That is, during the melting period ice floes break into smaller pieces and melt conserving their form (in the statistical sense).

Table 2. Means and standard deviations (sd) of geometric properties of ice floes with characteristic diameter greater than 0.1 km.

Case	Number of floes	Characteristic diameter (km)		Elongation		Shape factor	
		Mean	Sd	Mean	Sd	Mean	Sd
April 21	1478	0.368	0.525	1.70	0.87	0.73	0.15
May 19	1509	0.266	0.210	1.72	0.89	0.72	0.13

There are two ways to describe the distribution of the floe size, the number of floes or the areal coverage of floes as a function of the characteristic diameter. Here both are presented. Denote by $S(\lambda)$ the area of ice floes with $l \geqslant \lambda$; $S(0)$ is defined as the total area (including open water) and then the ice area becomes $S_+ = \lim_{\lambda \to 0^+} S(\lambda)$. Below we keep S_+ fixed and consider the distribution of floe size over this area.

Our data include individually only those floes with $l \geqslant l_0$. Their total number is

$$N = S(l_0)/\widetilde{A} \tag{4}$$

where the symbol »~» stands for averaging, and the number of floes in a size class $\lambda \leqslant l < \lambda + d\lambda$ is

$$n(\lambda) = Np(\lambda)\,d\lambda, \tag{5}$$

where p is the probability density of the number of floes. Eq. (5) can be written as

$$n(\lambda) = \frac{S(l_0)}{S_+} \cdot \frac{S_+}{\widetilde{A}}\, p(\lambda)\,d\lambda. \tag{6}$$

The ratio $S(l_0)/S_+$ is given in Table 1. It will be shown below that the shape factor is independent of the floe size; thus from Eq. (3) $\widetilde{A} = \widetilde{\kappa}\,\widetilde{l}$ and the numerical values can be obtained from Table 2. The function p can be estimated from the pictures, and then we can calculate the number of floes of different size in the area S_+.

A general feature in the distributions is that the exponential slope is decreasing when the floe size increases (Fig. 3). This was noted earlier for the same basin in LEPPÄRANTA (1981). During the time between our cases there was a clear reduction of floes with $l > 1$ km while at $l < 0.4$ km the opposite was true.

A weak point in the above description is that there is always some cutoff diameter below which individual floe data do not exist. When considering the areal coverage of floes all ice can be included in the same distribution (and, if wanted, also open water). This leads to the function $S(\lambda)$ itself. Of course, we cannot give the form of S for $\lambda < l_0$ but only the total change $S_+ - S(l_0)$. Hence empirical floe size statistics based on S should not depend on its form at $\lambda < l_0$. One possibility is to use fractiles.

Our results show clearly how large floes have disintegrated and the small floe group has taken over most of the area (Fig. 4). The 0.5-fractile (median) represents a typical floe size w.r.t. areal coverage. This was 2.1 km on April 21 and less than 0.1 km on May 19 – quite different from the averages over the number of floes

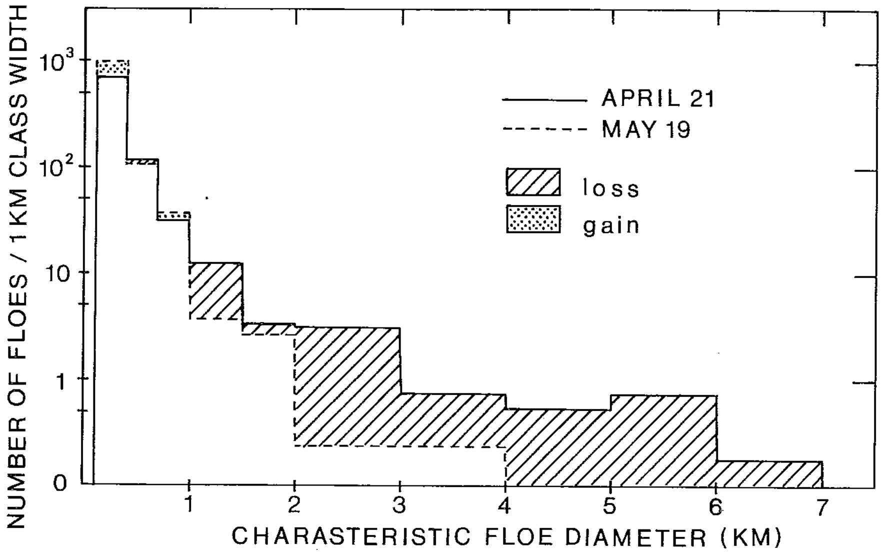

Fig. 3. The distribution of the number of ice floes scaled theoretically over a 1000 km^2 ice area (note: the actual number of observations is the vertical unit multiplied by 1.85 in April and by 2.32 in May.

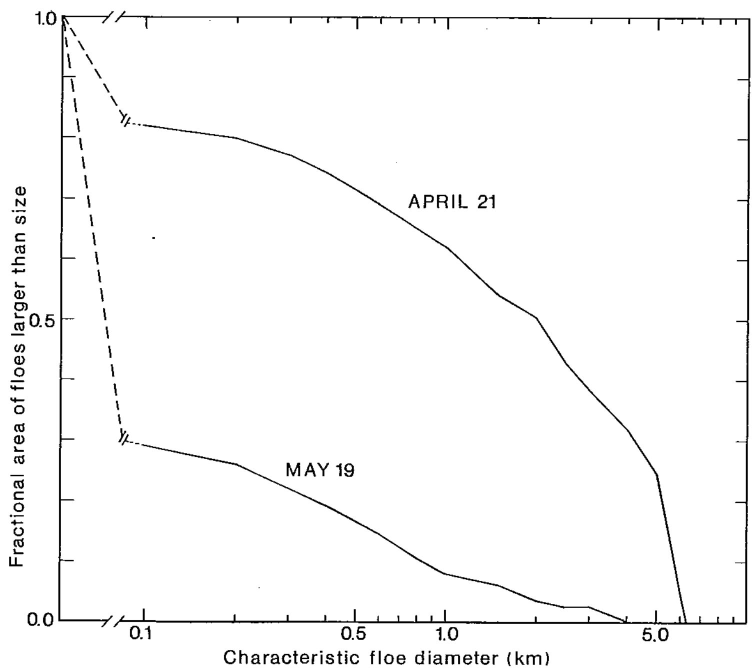

Fig. 4. The areal coverage of floes.

in Table 2. The 0.25 – fractile changed from 5.0 to 0.22 km.

The form of ice floes was statistically similar in both cases (Table 2). An »average floe» had the length ratio of about 1.7 between the major and minor axes and its surface area was slightly less than that of an ellipse with the same axes. However, the deviation from elliptic shape was not statistically significant – this gives us a mathematically simple working hypothesis.

An important result with respect to the form of ice floes was obtained: both the elongation and the shape factor were uncorrelated with the characteristic floe diameter. The form of the distributions indicated that this can be generalized to independence. Thus the statistical invariance of the form seems to hold both in the time and in the size domain. On May 19 the elongation and shape factor were for $l > 1$ km slightly less than for $l < 1$ km (Table 3) but the differences were not statistically significant. Thus, in the first approximation, all ice floes can be idealized having a fixed elliptic form.

Table 3. Mean elongation and shape factor for two size groups (l – characteristic floe diameter).

Case	Elongation		Shape factor		Number of floes	
	l<1 km	l>1 km	l<1 km	l>1 km	l<1 km	l>1 km
April 21	1.70	1.70	0.73	0.73	1398	80
May 19	1.73	1.48	0.72	0.68	1493	16

4. *Discussion*

Aerial photographs over pack ice in the Bothnian Bay have been studied here. The data include two cases in the melting season. The horizontal floe geometry was described with three parameters which could be relatively easily determined from the pictures: characteristic floe diameter, elongation and shape factor. The first one describes floe size and the other two floe form.

We consider the floe size distribution to be best described using the function S, $S(\lambda)$ equal to the areal coverage of floes with characteristic diameter greater than or equal to λ. Several reasons exist: 1) floes smaller than the cutoff diameter (which is always present) can be nicely included in the distribution; 2) the distribution can be easily extended to include open water (floe diameter equal to zero) if wanted; 3) in mesoscale ice mechanics the areal coverage is evidently more meaningful than the number of floes.

In our two cases there was a big difference in the floe size distributions (Fig. 4). During the time between them very large floes disintegrated and the fractional area of small floes increased substantially. However, in the diameter range 0.1 to 1 km there were only minor changes. These data are not enough to suggest any simple analytic form – or reject all – for the distribution. One might think that there can be modes in the neighbourhoods of both ends of the distribution and hypothesize as follows: in the very beginning of the melting season only the big floe mode exists and when the time goes on the small floe mode develops and the other disappears.

In pack ice dynamics a continuity equation for S is needed. This has a general form

$$\frac{DS}{Dt} = \Phi + \Psi, \tag{7}$$

where D/Dt is the material time derivative and Φ and Ψ describe changes in S due to thermal and mechanical effects, respectively. In general one has to include both integration and disintegration of floes but for the melting season one can assume (although not exactly true) that the size of floes does not increase. Then Eq. (7) can be written as

$$\frac{DS}{Dt} = \frac{d\lambda}{dt} \cdot \frac{dS}{d\lambda} + \Psi. \tag{8}$$

Here the factor $d\lambda/dt$ represents lateral melting. The function Ψ describes the production of new floes when a floe breaks. One should note that Eq. (8) is analogous with the continuity equation of ice thickness distribution presented by THORNDIKE *et al.* (1975).

The form of ice floes was observed to be in the statistical sense invariant both in the time and in the size domain which gives a nice starting point for mathematical treatment of mesoscale pack ice phenomena involved with floes. Typically floes were almost ellipses with elongation less than about 2.5. A general elliptic shape would not be rejected by the present data and can hence be taken as a basic assumption in theoretical work. This fixes the shape factor κ to $\pi/4$ and leaves the elongation free. If one wants a fixed form, the elongation can be set equal to, *e.g.*, 1.7 obtained in this work. If, on the other hand, a variable form is needed, a range can be given to the elongation. Our results suggest that the variations can be considered random.

We must note that our results may include features which are typical for the Bothnian Bay but not for an arbitrary basin. Even for the Bothnian Bay we have only two cases. However, earlier characterization of ice floes in the Bothnian Bay in April 1978 and 1979 (LEPPÄRANTA, 1981), based on aerial photographs supports our results on the form and size distribution of ice floes in April.

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