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ON THE CONTRIBUTION OF SEA ICE RIDGES INTO THE MASS OF ICE IN THE GULF OF BOTHNIA

by

WLODZIMIERZ P. ZAKRZEWSKI

Present affiliation: Division of Meteorology, Department of Geography, University of Alberta, Edmonton, Alberta, Canada

Abstract

General presentation of sea ice ridges in the Gulf of Bothnia is given. To examine the ridged ice effect on the ice mass in the basin it was assumed that the northern part of the Gulf of Bothnia is covered with level ice which was piled up into ridges during the single event of ridging, After formation of the ridges a shore lead has been established. Formula for the width of the shore lead was derived. Based on the published data of ridge morphology and mean ridge density the distribution of ice mass after ridging was investigated. It was found that for assumed grid net (grid cell size 10 x 10 km) the ice mass withing the field of deformed pack ice increased more than twice. The ridged ice contribution into the total mass of ice was equal to 60 %.

Similar computations have been done for the end of winter when the level ice between ridges and in the refrozen lead reaches its maximal thickness. Ice mass within any grid cell was compared with the mass of level ice of maximal thickness but without any ridges. Ridged ice contribution into the total mass of ice within any grid cell was examined. It decreased significantly because of the growth of level ice during the winter. Ridged ice contribution into total ice mass was equal to 48 and 33 % for any grid cell located within the field of deformed pack ice and for the whole basin, respectively.

It was shown that the mass of ridged ice affects the velocity field in numerical model of ice drift in the Gulf of Bothnia. For operational purposes remoting the ice topography by laser profilometer is recommended to give good estimation of the mass of ice in the basin.

1. *Introduction*

The knowledge of the amount of ice mass in a given water basin is necessary when the ice budget is considered (KELIHER and FOLEY, 1984; ZAKRZEWSKI and GRABOWSKA, 1982) and/or the mass field is calculated in the numerical models of the ice dynamics (*e.g.* LEPPÄRANTA, 1981a).

Below some remarks on the calculation of the ice mass are presented. A small water basin with first-year sea ice has been considered. The northern part of the Gulf of Bothnia was chose to be the most adequate for this study because of the high concentration of pack ice there and the common occurrence of ridges.

2. *General presentation of ridges in the Gulf of Bothnia*

Ridges have been investigated often in the Baltic (PALOSUO, 1975; LEPPÄRANTA, 1981b; KEINONEN, 1976, 1977, 1978). Hence, their morphology and morphometry is well known. The characteristic parameters of the ridge size are: the height of the sail, the depth of the keel, the thickness of ice blocks in the rubble, the porosity of the sail and keel, and the ridge width. The typical shape of ridges is presented in Fig. 1. According to earlier publications the values of above mentioned parameters have been extracted in Table 1.

Diving tests and careful measurement procedures let PALOSUO (1975) and KEINONEN (1976, 1977 and 1978) examine ridge profiles (Fig. 2). The maximum total thickness of the ice ridges in the Gulf of Bothnia reported by PALOSUO (1975) is equal to 31.4 m (keel depth 28 m). The mean thickness of ice ridges penetrated by ships during the years 1974 to 1977 is equal to 10 m (KEINONEN, 1978). However, the smaller ridges are encountered very often in the Gulf of Bothnia.

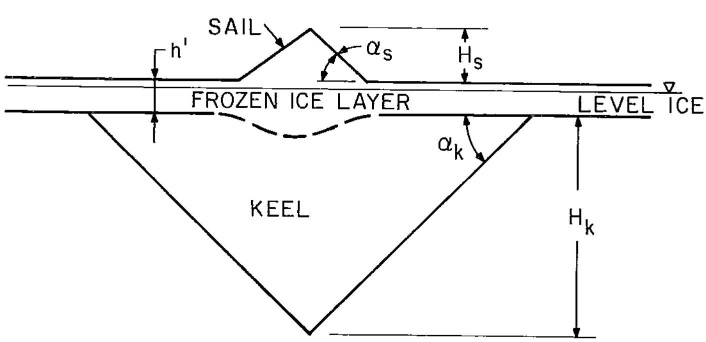

Figure 1. Vertical cross-section of an ice ridge.

Table 1. Selected characteristics of ridges in the Gulf of Bothnia.

Parameter	Range/the most common value		Reference
Sail			
ice density	870 – 914/870	(kg/m^3)	Keinonen (1977, 1978)
porosity	36 – 43/N.A.★	(%)	Keinonen (1977, 1978)
ice block thickness	0.2 – 0.4/0.31	(m)	Keinonen (1978)
height	0.25 – 3.42/1.44	(m)	Keinonen (1976) and Palosuo (1975)
Keel			
ice density	N.A./870	(kg/m^3)	Keinonen (1978)
porosity	36 – 43/N.A.	(%)	Keinonen (1978)
ice block thickness	0.2 – 0.4/0.31	(m)	Keinonen (1978)
depth	7 – 28/N.A.		Palosuo (1975)
Total ridge thickness	≤31.4/10	(m)	Palosuo (1975), Topp (1976) and Keinonen (1978)

★ N.A. – Not available

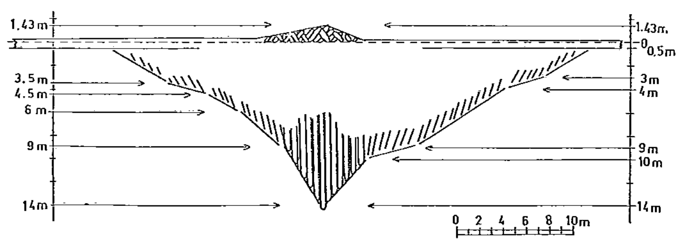

Figure 2. Profile of ice ridge in the Gulf of Bothnia (PALOSUO, 1975).

3. *Estimation of ice mass in the Gulf of Bothnia*

Let us assume that the northern part of the Gulf of Bothnia is covered by level ice (fast ice and consolidated and/or compact pack ice) of uniform thickness as presented in Fig. 3a. The mass of ice in any grid cell can be estimated by

$$m'_{ij} = \rho \cdot h' \cdot S_{ij} \tag{1}$$

where ρ is the ice density, h' is the level ice thickness and S_{ij} is the total surface of ice in a given grid cell (ij).

The total mass of ice in the basin is equal to the sum of m'_{ij} over the grid. As-

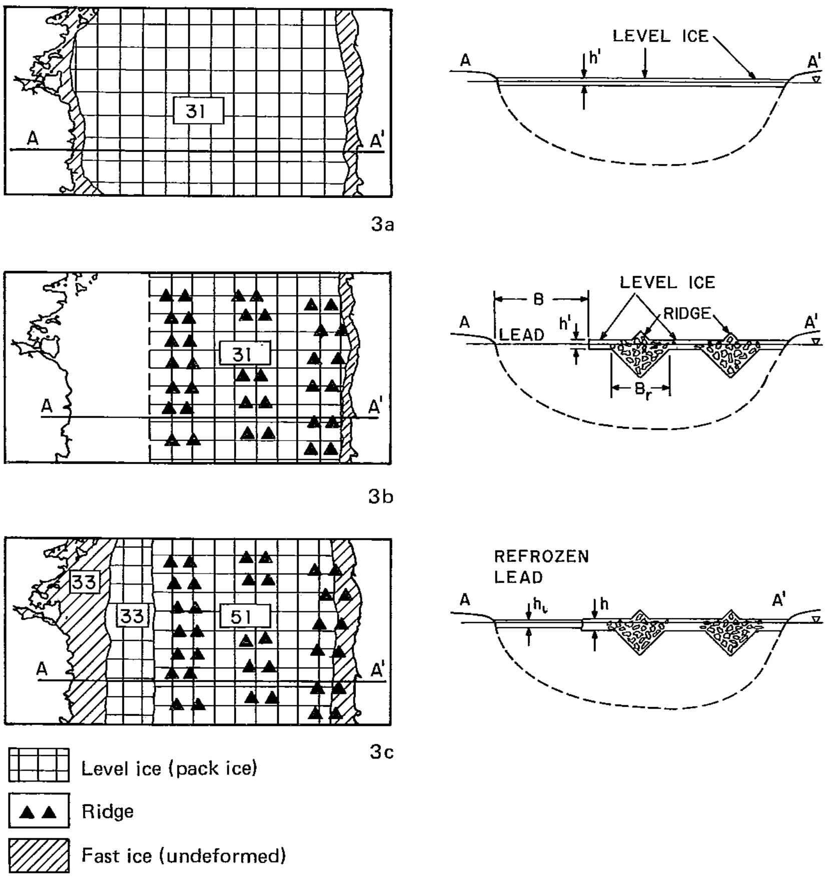

Figure 3. Assumed ice situation in the Gulf of Bothnia before the event of ridging (a), soon after the formation of the ridges (b), and at the end of winter (c).

suming the complete covering of the water basin with ice the total mass is

$$m' = \rho \cdot h' \cdot k \cdot n \cdot \Delta x \cdot \Delta y \quad (2)$$

where Δx and Δy are the grid sizes in x and y direction, respectively. Here we take $\Delta x = \Delta y$ (Fig. 4).

To calculate the mass of ice in the ridges we assume the ideal linear course of ridges across the whole basin precisely parallel to the y direction. If strong and long-lasting westerly winds occurred such ridges would be formed first of all in the eastern and central parts of the basin as shown in Fig. 3b.

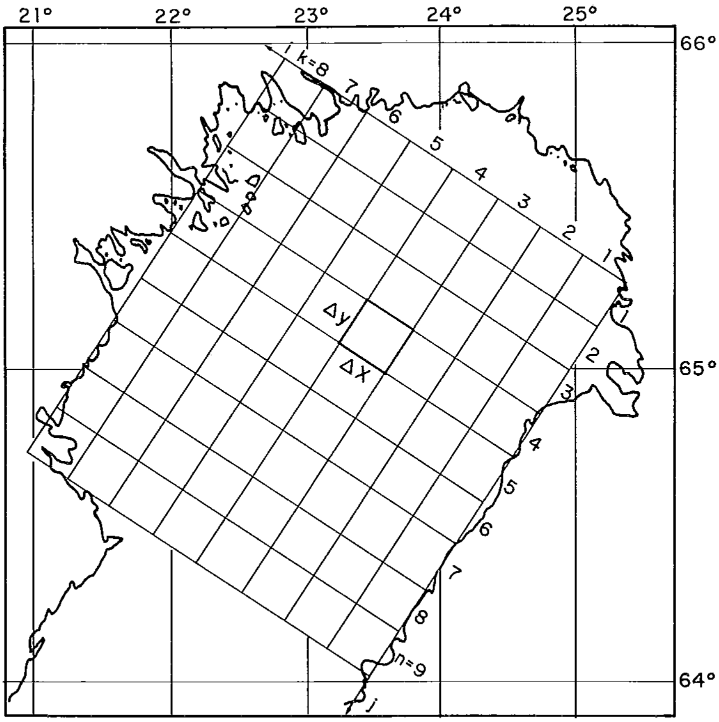

Figure 4. Grid net used for computations of the ice mass in the Gulf of Bothnia.

The total mass of a single ridge link is equal to

$$m_r = \rho \cdot L_r \cdot A_r \cdot d \tag{3}$$

where A_r is the surface area of the cross section of the ridge, d is the ice block compactness coefficient for the rubble, and L_r is the length of a ridge. If the ridge length is equal to the length of the basin, we have

$$m_r = \rho \cdot n \cdot \Delta x \cdot A_r \cdot d \tag{4}$$

The ridge is formed by the ice blocks originating from the level ice. As a result of ridging, the ice cover in the basin has been diminished as it is shown in Fig. 3b, and the lead parallel to the western coast has been established. When the size of a ridge is determined, the lead width increment due to the single ridge formation can be expressed by

$$B' = m_r/\rho \cdot h' \cdot L_r = A_r \cdot d/h' \quad (5)$$

The lead width increment B' is thus related to the cross sectional area of a ridge (A_r) and to the thickness of level ice (h'). Field data reported from the Gulf of Bothnia let TOPP (1976) and LEPPÄRANTA (1981a, 1981b) estimate the spatial distribution of ridges. They used the parameter called the ridge density (μ) which presents the number of ridges per 1 km of a track. Its value for a given area increases as winter passes because new ridges are formed in the basin during heavy winds blowing over the ice cover. The ridge density varies from winter to winter because of the variations of atmospheric circulation and the ice thickness. For the Gulf of Bothnia the mean value of the ridge density is equal to 1.25/km in TOPP (1976) and 5–10/km in LEPPÄRANTA (1981b). Topp's data were visual observations based on 3600 km of track penetrated by ships and LEPPÄRANTA (1981b) used laser profilometer records. When ridged ice zones were only considered the mean value of μ was equal to 4.9/km (TOPP 1976). Topp's data originated from the winter 1975/76 when severe storms were not common. In a typical winter with the deep lows and strong winds passing over the Baltic Sea plenty of ridges are thought to be formed. Hence, the values reported by LEPPÄRANTA (1981b) seem to be adequate for the Gulf of Bothnia.

If the mean ridge density is determined for the whole basin the total width of a lead formed due to the single event of ridging in the considered ice cover can be found by comparison the mass of level ice before ridging with the mass of ice in ridges and level ice between ridges. We may also compare the cross sectional areas of the ice in the direction perpendicular to ridges in the basin before and after ridging. Then,

$$S_l = S_r + S_u \quad (6)$$

where S_l is the cross sectional area of level ice before ridging, and S_r and S_u is the cross sectional area of ridges and undeformed ice between them, respectively. Thus,

$$(k \cdot \Delta x - B) \cdot \mu \cdot \left[A_r \cdot d + h'\left(\frac{1}{\mu} - B_r\right)\right] = k \cdot \Delta x \cdot h' \quad (7)$$

where $(k \cdot \Delta x - B) \cdot \mu$ is number of ridges in the basin, B is the ice lead width (in meters), μ is the ridge density (m^{-1}), B_r is the ice ridge width, and $A_r \cdot d$ is the cross sectional area of ridge (in square meters). Finally,

$$B = \frac{k \cdot \Delta x \cdot \mu(h' \cdot B_r - A_r \cdot d)}{\mu \cdot h' \cdot B_r - h' - \mu \cdot A_r \cdot d} \quad \text{m} \tag{8}$$

Lead width is proportional to the size of the grid net in x direction, the length of grid cell and ridge density as well as the cross sectional area of ridge. It is inversely proportional to the ice ridge width and the thickness of level ice.

Just after formation of the ridges, the total mass of ice in the basin is not change but the mass distribution is strongly affected by the ridging. The ice occurs only in z columns of the grid net ($1 \leqslant z \leqslant k$) where z is the integer value from the following term

$$z = \mathrm{INT}\left(\frac{k \cdot \Delta x - B}{\Delta x} + 1\right) \tag{9}$$

The grid cells for $i = 1, ..., z-1$ are full of ice but in the zth column of a grid net any grid cell is partly covered by ice only. The mass of ice in each grid cell for $i = 1, ..., z-1$ is equal to

$$M' = (\Delta x)^2 \mu \cdot \rho\left(A_r \cdot d + h'\left(\frac{1}{\mu} - B_r\right)\right) \tag{10}$$

and for each of n grid cells located in the zth column the mass of ice is equal to

$$M^\star = \frac{B - (k - z)\,\Delta x}{\Delta x} M' \tag{11}$$

Now it is easy to present the distribution of the ice mass in the basin after ridgir For the grid net the ratio of the ice mass after and before ridging can be calculated from

$$c'_{ij} = \begin{cases} M_{ij}/m'_{ij} & \text{for } j = 1, ..., n \text{ and } i = 1, ..., z-1 \\ M^\star_{ij}/m'_{ij} & \text{for } j = 1, ..., n \text{ and } i = z \\ 0 & \text{for } j = 1, ..., n \text{ and } i = z+1, ..., k \end{cases} \tag{12}$$

The contribution of the ridged ice into the total mass of ice for any grid cell is expressed by formula

$$f'_{ij} = \frac{A_r \cdot d}{A_r \cdot d + h'\left(\frac{1}{\mu} - B_r\right)} \qquad \text{for } j = 1, ..., n \text{ and } i = 1, ..., z \tag{13}$$

which describes the ratio of the mass of ridged ice to the mass of all ice within each grid cell while Eq. (12) presents the ratio of all ice within the grid cell after ridging to the mass of level ice there before ridging.

For the grid cells located along the pack ice edge ($j = 1, ..., n$ and $i = z$) the fraction f'_{ij} is the same as for other cells located within the field of ridged ice.

The ice situation in the basin changes as the time passes. The lead becomes refrozen. The ice there reaches its maximum thickness at the end of winter (usually in March). The growth of a level ice in the area between the ridges is also remarkable but the ice-growth rates are smaller than that of level ice in the refrozen lead because of the initial ice thickness effect on the heat conductivity. Assuming the maximum ice thickness in the lead equal to h_l and the maximum ice thickness of the level ice in the ridged ice zone h (Fig. 3c), and neglecting the change of mass of any ridge, one can find that for any grid cell located in full within the field of ridged ice the mass of all ice is equal to

$$M'' = (\Delta x)^2 \cdot \mu \cdot \rho \cdot \left(A_r \cdot d + h\left(\frac{1}{\mu} - B_r\right)\right) \tag{14}$$

For the grid cells located in full within the refrozen lead the total ice mass in each cell can be calculated by

$$M_l = (\Delta x)^2 h_l \cdot \rho \tag{15}$$

For the grid cells located partly within the ridged ice field and partly within the refrozen lead, the total mass of ice in each grid cell is equal to

$$M^{\star\star} = \frac{B - (k-z)\Delta x}{\Delta x} M'' + \frac{\Delta x(k-z+1) - B}{\Delta x} M_l \tag{16}$$

As the values of the ice mass for all cells of the grid net are presented by Eqs. (14–16), the total mass of all the ice in the basin at the end of winter can be calculated by

$$M_T = \sum_{j=1}^{n} \sum_{i=1}^{z-1} M''_{ij} + \sum_{j=1}^{n} M^{\star\star}_{i=z,j} + \sum_{j=1}^{n} \sum_{i=z+1}^{k} (M_1)_{ij} \tag{17}$$

To estimate the contribution of ice ridges into the mass of the ice, we assume that the whole basin is covered by level ice of thickness h at the end of winter. Then the mass of ice in the whole basin is

$$M_e = n \cdot k \cdot h \cdot \rho(\Delta x)^2 = n \cdot k \cdot m_e \tag{18}$$

Hence, for the end of winter the ratio of the mass of ice occurring in any grid cell to the assumed ice mass m_e is equal to

$$C''_{ij} = \begin{cases} M''_{ij}/m_e & \text{for } j = 1, \ldots, n \text{ and } i = 1, \ldots, z = 1 \\ M^{**}_{ij}/m_e & \text{for } j = 1, \ldots, n \text{ and } i = z \\ (M_l)_{ij}/m_e & \text{for } j = 1, \ldots, n \text{ and } i = z+1, \ldots, k \end{cases} \tag{19}$$

Consequently, the ratio of ice mass occurring in the whole basin when the ridges are taken into consideration to the case when they are neglected, is equal to

$$C_T = M_T/M_e \tag{20}$$

where M_T and M_e are presented by Eqs. (17) and (18), respectively.

Now we can consider the contribution of the ridged ice into the total mass of all the ice within any grid cell. There are no ridges in the refrozen lead ($j = 1, \ldots, n$ and $i = z + 1, \ldots, k$) but for the other grid cells the ridge contribution is presented by

$$f'' = \begin{cases} \dfrac{A_r \cdot d}{A_r \cdot d + \left(\dfrac{1}{\mu} - B_r\right)h} & \text{for } j = 1, \ldots, n \text{ and } i = 1, \ldots, z-1 \\[2ex] \dfrac{A_r \cdot d \cdot \mu \cdot F}{A_r \cdot d \cdot \mu \cdot F + (1-F)h_l + \mu \cdot h \cdot F\left(\dfrac{1}{\mu} - B_r\right)} & \text{for } j = 1, \ldots, n \text{ and } i = z \\[2ex] 0 & \text{for } j = 1, \ldots, n \text{ and } i = z+1, \ldots, k \end{cases} \tag{21}$$

where the term $F = \dfrac{B - (k-z)\Delta x}{\Delta x}$ presents the fraction of the grid cells (for $i = z$) covered by the thick pack ice including ridges, and the term $(1 - F)$ presents the fraction of such grid cells covered by the level ice in the refrozen lead. The mean value of the f'' fraction is calculated for the whole basin by

$$f''_T = \frac{(k \cdot \Delta x - B)\mu \cdot A_r \cdot d}{(k \cdot \Delta x - B)\mu\left(A_r \cdot d + h\left(\dfrac{1}{\mu} - B_r\right)\right) + B \cdot h_l} \tag{22}$$

where h and h_l is the thickness of level ice between the ridges and in refrozen lead, respectively, and all the other terms are the same as of Eq. (8).

4. *Results and discussion*

To estimate the contribution of ice ridges into the ice mass in the Gulf of Bothnia some computations have been done. For this purpose some field data have been employed (Table 2).

Table 2. Ridge parameters used for computations.

Parameter	Value
Ice density (ρ)	870 kg/m^3
Total ridge thickness (H)	10 m
Sail	
shape	triangle
slope angle (α_s)	30°
height (h_s)	1.34 m
compactness coefficient (d_s = 100 % – porosity)	60 %
ice block thickness (h')	0.31 m
Keel	
shape	triangle
slope angle (α_k)	30°
depth (h_k)	8.66 m
compactness coefficient (α_k = 100 % – porosity)	60 %
ice block thickness (h')	0.31 m
Other	
mean ridge density (μ)	0.005 m^{-1}
water density (ρ_w)	1005 kg/m^3

As the characteristic parameters describing a ridge, the total ridge thickness H, and slope angles of sail (α_s) and keel (α_k) have been chosen. α_k was assumed to be equal to mean value of slope angles of ice keels investigated by PALOSUO (1975, p. 52). It was equal to 31.3° and approximated by $\alpha_k \cong 30°$. The slope angle for the sail was assumed to be the same. Hence, $\alpha_k = \alpha_s = \alpha \cong 30°$.

To calculate the cross section area (A_r) of a ridge and the maximal keel width (B_r), the values of the sail height (H_s) have to be known. For given ice density (ρ) and water density (ρ_w) they could be obtained from equations

$$H = H_s + H_k$$
$$\frac{H_s}{H_k} = \frac{d_k(\rho_w - \rho)}{\rho \cdot d_s} \tag{23}$$

where d_s and d_k are the coefficients of ice blocks compactness in the sail and keel, respectively. The ice blocks compactness coefficients for the sail (d_s) and for the keel (d_k) have been reported to be the same (KEINONEN, 1978).

For ρ = 870 kg/m^3 and ρ_w = 1005 kg/m^3 the sail and keel heights have been computed (H_s = 1.34 m and H_k = 8.66 m) as well as the ridge width $B_r = 2H_k \mathrm{ctg}\alpha = 30.00$ m. The mean cross section surface of such ridge was equal to $A_r = H_s^2 \cdot \mathrm{ctg}\alpha(1 + (\rho/(\rho_w - \rho))^2) = 132.3$ m^2, and after correction by the rubble compactness coefficient (d = 60 %) the value of $A_r \cdot d$ = 79.4 m^2.

The thickness of the level ice has been extracted from KEINONEN (1976, 1977 and 1978) and assumed to be equal to h' = 0.31 m during ridging and maximally equal to h = 0.51 m at the end of winter. The maximum level ice thickness in the lead (h_l) was calculated using ZUBOV's (1945) practical ice growth rate formula. Based on initial thickness of the ice cover h' = 0.31 m just after ridging and its maximal thickness h = 0.51 m at the end of winter, the number of degree – day frost has been estimated for the period of the ice growth. Then, the maximal ice thickness for the refrozen lead was obtained to be equal to 0.33 m.

As the ridges characterized by parameters shown in Table 2 had been formed, the ice mass distribution was changed (Fig. 5) and this can be calculated using Eqs. (2, 8–12). If these changes of the ice mass distribution are neglected in any operational forecasting model, the results are strongly affected and the accuracy of the velocity field decreases. The quantitative error in the pack ice concentration

i	8	7	6	5	4	3	2	1
	NO ICE 0.65)	NO ICE (0.65)	NO ICE (0.65)	NO ICE (0.65)	0.52 (0.89)	2.13 (1.63)	2.13 (1.63)	2.13 (1.63)

j

Figure 5. Ratio of ice mass when the effect of ridges is considered to the mass of the level ice. Numbers in brackets refer to the ice situation at the end of winter; numbers without brackets to the situation immediately after ridging.

field is resulted by the lead formation and need not be tolerated at all. Hence, the tendency to tracking the ice concentration field and ice topography by remote sensing is really proper. Well known operational LEPPÄRANTA's (1981a) ice drift model was run for the northern part of the Gulf of Bothnia. The air drag coefficient of the level pack ice was assumed to be equal to $C_1 = 1.4 \cdot 10^{-3}$. Value of the air drag coefficient for deformed pack ice was computed by formula (DORONIN and KHEISIN, 1975)

$$C = C_1 \left(1 + \frac{C_r}{C_1} N_r\right) \tag{24}$$

where $C_r = 3.4 \cdot 10^{-2}$ (DORONIN and KHEISIN, 1975) is the resultant air drag coefficient of ridges (for wind blowing perpendicular to the ridge link), and N_r is the ratio of surface area of ridges to the total surface area of pack ice in a given location. For assumed ridge morphology we have $N_r \cong 0.023$ and $C \cong 2.2 \cdot 10^{-3}$. For these values of air drag coefficient the computed velocities of ice drift were underestimated by 9—12 % when the level pack ice was considered instead of deformed ones.

For the conditions at the end of winter, the ice mass distribution has been also computed (Eqs. 14—18). As it is shown in Fig. 5, neglecting the ridges produces large errors in the mass field. Large errors occur also when the total ice mass is calculated by Eq. (18) instead of (17). The real value of the ice mass is underestimated by 5 %. The contribution of the ridged ice mass into the total mass of ice occurring in any grid cell as well as in the whole basin has been calculated for the moment following the event of ridging and for the end of winter according to Eqs. (13, 21 and 22), respectively. The ridged ice contribution into the total ice mass is uniform under assumed by us conditions and equal to 60 % (Fig. 6) for the moment following the ridging, while its distribution is not uniform for the end of winter. Ridged ice contribution into the ice mass reaches then 48 % in

i	8	7	6	5	4	3	2	1
	NO ICE (0)	NO ICE (0)	NO ICE (0)	NO ICE (0)	60 (21)	60 (48)	60 (48)	60 (48)

j

Figure 6. Percentage contribution of ridged ice into the mass of ice in the Gulf of Bothnia. Numbers without bracket refer to the situation immediately after ridging; numbers in brackets refer to the end of winter.

the area of thick deformed pack ice but it decreases to 21 % for the grid cells along the edge of the deformed pack ice*), and it is equal to 0 for the grid cells located within the refrozen lead. For the whole basin this parameter is equal to 3 % only. That is, the increased thickness of level ice in the area between the ridges and in the refrozen lead strongly affected the ridged ice contribution. It

*) this value was obtained for grid size $k = 8$ and $\Delta x = 10000$ m.

should be noted that the ridged ice contribution into the total mass of ice is mostly affected by the ridge density (μ) and the cross sectional area of ridges (A_r) (see Eqs. 13 and 22).

Determination of the contribution of ridged ice into the total mass of ice is the most convenient if the input data for ridge density came from the remote sensing surveillance (*e.g.* by the air-borne microwave altimeter). However, the cross sectional area of the ridges has to be computed from the assumed input parameters. The height of a ridge sail is rather convenient for this purpose, and it can be easily measured using remote sensing techniques (analysis of the stereo-photographs, oblique photographs or altimeter data). The cross sectional area of a ridge is proportional to the square of the height of its sail. Therefore, as the ridge density and the heights of the ridge sails increase, the ridged ice contribution into the total mass of ice increases.

Presented results proved how large is the contribution of ridges into the total mass of pack ice when the shore leads induced by ridging are ice free as well as when they are refrozen. In the operational practice ice models should be fed in reel time with the input data collected from the remote sensing surveillance. In addition to the routine data collected by the icebreakers and shore stations, satellite and air-borne photography should be employed for detection of the leads and other openings in the ice soon after their formation. Ice topography measurements by the microwave altimeter and SLAR are recommended for current operational practice. The latter measurements will be helpful in addition to the ice mass field calculations also to the selection of a representative value of the air drag coefficient for the pack ice.

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