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ABSOLUTE GREATEST THICKNESS OF LEVEL ICE ON THE BALTIC SEA

by

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Abstract

The absolute greatest ice thickness on the Baltic Sea occurred during the severe winter of 1941/42. Thicknesses up to 115 cm were measured in the northern Bay of Bothnia, and 80 to 100 cm was recorded in the Gulf of Finland. Along the coast of the Sea of Bothnia and in the northern parts of the Archipelago Sea a thick snow cover kept the ice relatively thin (c. 70 cm), although thicknesses of almost 90 cm had been recorded in these areas the previous winter (1940/41).

The growth of level, ''black ice'' is affected mainly by the heat exhange with the atmosphere and by the thermal insulation provided by the snow cover. A slowing down in the rate of growth of ice thickness was, however, observed in the early part of winter along the Finnish coast due to the flow of warmer water beneath the ice from the direction of the open sea.

1. *Variations in the maximum ice thickness from winter to winter*

Observations of ice for the winters of the 60 years period from 1919/20 to 1978/79 were selected from archives of the Institute of Marine Research. During this period ice thicknesses had been measured about once a week along the Finnish coast (JURVA, [3]). In general the ice thicknesses were presented exatly, whereas in the case of the snow cover, the depths were given as maximum and minimum values in case of drifting. Measurements of ''white ice'', formed from snow cover on top of the ice, began in winter 1962/63.

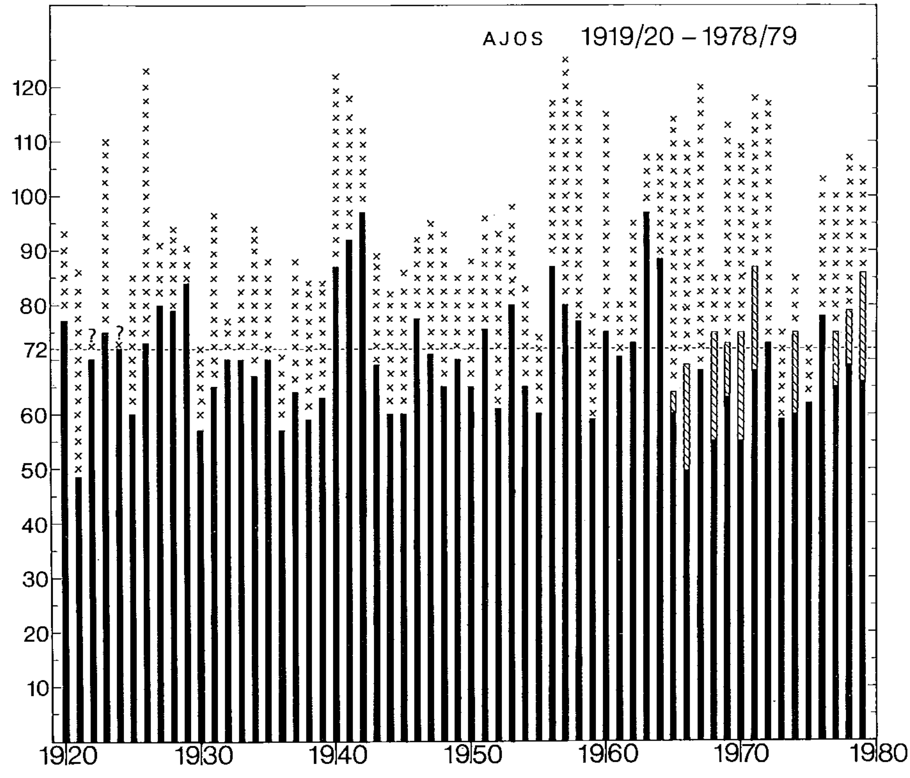

Fig. 1. The maximum ice thicknesses (columns) and the depths of snow (crosses) in Ajos during the winters 1919/20—1978/79. White ice (hatched) has been observed the winter 1962/63.

The sum of the negative daily air temperatures, of shortly "frost sum", is greater in the northern Bay of Bothnia than in other sea areas (Palosuo, [8]), and it is in this region that higher maximum ice thickness are recorded. Thus the maximum thicknesses at Ajos in Kemi (Fig. 1) varied from 48 to 97 cm, with a mean value of 72 cm. The depth of the snow cover on the ice during the same period had a mean value of 26 cm. White ice was not formed every winter at Kemi, although in some winters thicknesses of up to 40 cm were recorded (Palosuo, [7]). A corresponding comparison can be made of the measurements taken at the Barösund-Bågaskär stations on the Gulf of Finland (Fig. 2), where the maximum thicknesses varied from 3 to 80 cm, with a mean value of 38 cm. The corresponding snow depth was 15 cm. The greates thickness of white ice was 28 cm, although white ice formed only something like one year in every two.

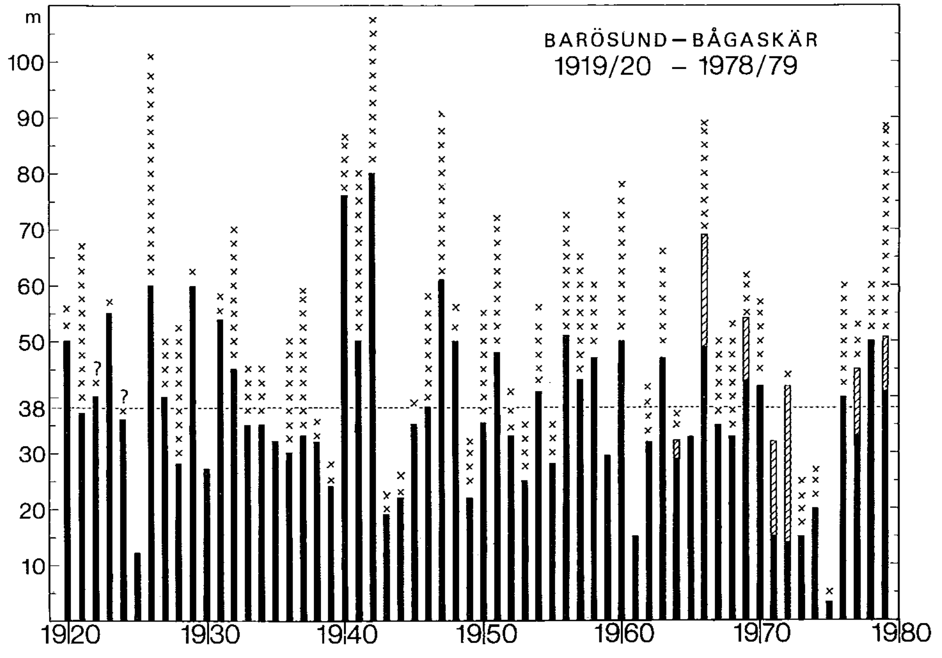

Fig. 2. The maximum ice thicknesses and depths of snow in Barösund during the winters 1919/20—1961/62 and in Bågaskär 1962/63—1978/79.

3. *Regional distribution of maximum ice thicknesses*

As already pointed out, the absolute greatest ice thicknesses measured in the winter of 1941/42 were higher than during the other years of the period study. For this reason the regional distribution of the ice thicknesses during this winter was studied. The study was based on the measured values, and values for the other parts ot the shipping fairway were obtained by interpolation and extrapolation. Thus, in the case of the fairway leading from Kemi to the open sea, it was possible to make use of measurements taken at both Kemi Middle Roadstead and at Ajos, as well as measurements from Röyttä and Kuusiluoto (in Tornio) and from Kraasukka (in Haukipudas). The results are presented in the form of a chart (Fig. 3). The chart shows clearly that the highest maximum ice thickness of 115 cm occurred in the arhipelago between Tornio and Kemi and extended right up to the north of Hailuoto. Further south, the maximum value of 70 cm recorded along the coast of the Sea of Bothnia and in the northern parts of the Archipelago Sea was smaller than 90 cm recorded the previous winter (1940/41) as a result of the deep snow cover. Use of the formulae presented below shows that in absence of thick snow cover the ice thickness would have achieved a value of 90 cm in these areas in the winter of 1941/42.

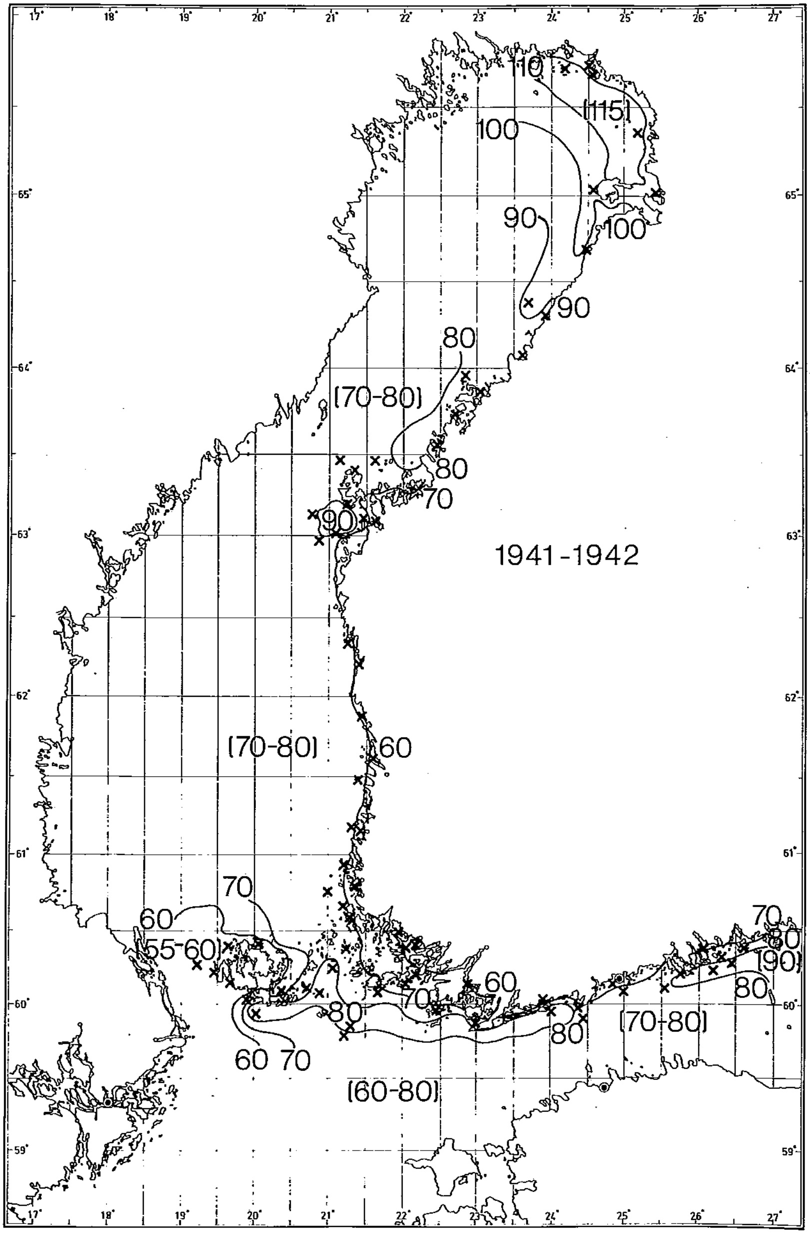

Fig. 3. The maximum ice thicknesses along the Finnish coast during the winter 1941/42. (The crosses mark the observations places.)

As far as the open sea is concerned, virtually no observations were made in the winter of 1941/42, since winter navigation was at that time poorly developed and because the problems posed by the war. The values given are based on information received from outer lighthouses as Ulkokalla, Valassaaret, Norrskär, Strömmingsbådan, Säppi, Isokari, Sälskar, Märket, Lågskär, Utö, Bengtskär, Porkkala Kallbådan, Söderskär and Orrengrund, where the men were able to venture onto ice during calm weather to hunt seals and at the same time to measure the thickness of the ice.

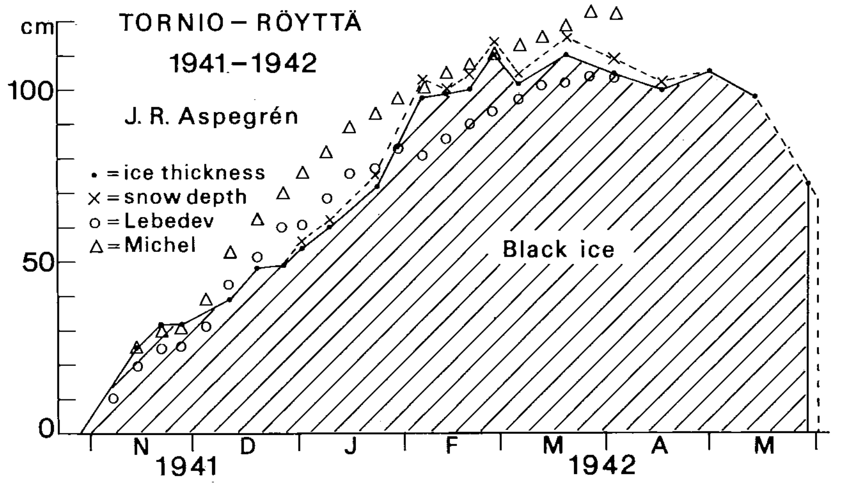

Fig. 4. The ice thicknesses (black dots) and snow depths (crosses) at Röyttä in Tornio during the winter 1941/42. (Open circles and triangles are calculated values according Lebedev's and Michel's equations.)

A closer examination of the way in which the absolute greatest ice thickness develops (Fig. 4) shows that at Röyttä in Tornio the ice was virtually devoid of snow cover throughout the winter. As in the spring of 1979, a certain amount of white ice often forms as a result of the melting of snow (Fig. 5), and this causes a temporary increase in the ice thickness value. When white ice formed early in the winter (Fig. 6) it had no decisive effect on the maximum thickness (Jones, [2]). In the case of observations on the snow, however, the issue was not quite so straightforward, since many observers, such as those at Virpiniemi in the winter of 1978/79, gave figures for both maximum and minimum depths of drifted snow (Fig. 5). Neither were there any measurements of the density of the snow, although density usually increased with the approaching spring. At Ajos in Kemi (Fig. 6) the snow was seen to be loose throughout early and mid-winter in 1955/56, but in the spring strong winds packed it denser. Fresh falls of snow produced a loose snow layer on top of the old snow. The effects of strong winds like this are often seen early in the winter.

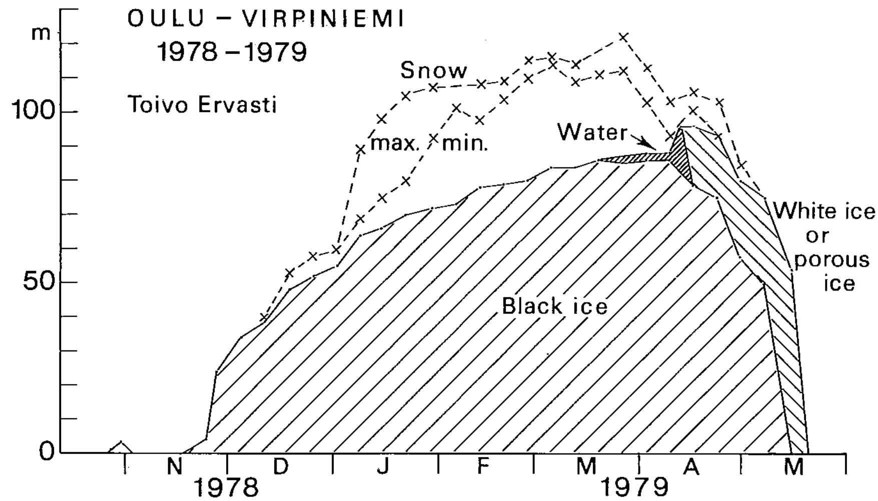

Fig. 5. The thicknesses and snow depths at Virpiniemi close to Oulu during the winter 1978/79.

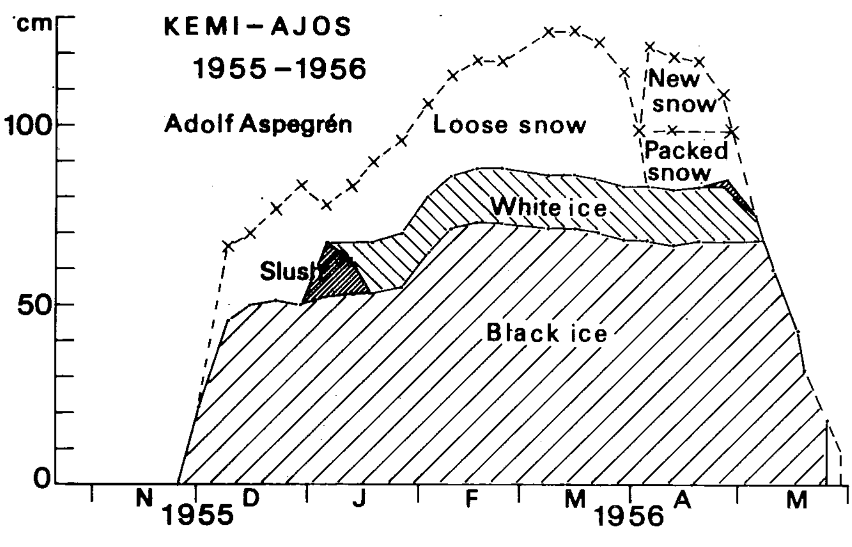

Fig. 6. The ice thicknesses and snow depths at Ajos in Kemi during the winter 1955/56.

4. *Theoretical calculation of the ice thickness*

In order to calculate the thickness of the ice, the heat transport trough the ice and the snow cover must be calculated, as Maykut and Untersteiner [5] did in the case of Arctic Sea. However, the formulae used contain terms which are not normally measured in routine observations of ice thicknesses. We must thus rely on abbreviated methods or empirical formulae.

Of the many empirical formulae, perhaps the most suitable is that derived by LEBEDEV [4], which has the following form:

$$h_i = 1.245\ (S)^{0.62}\ h_s^{-0.15} \tag{1}$$

where h_i = ice thickness
h_s = snow depth
S = "frost sum"

The term "frost sum" refers to sum of negative daily mean air temperatures calculated from the time of freezing to the time of measuring the ice thickness or mathematically expressed:

$$S = \int_{\tau_o}^{\tau} (t_a - t_f)\, d\tau \tag{2}$$

where t_a = ambient temperature
t_f = freezing point temperature
τ = time

Although Lebedev originally used this formula to calculate the thickness of fresh water ice, the formula also seems to hold good for the brackish water of the northern Baltic Sea. The values calculated using Lelbedev's formula for Röyttä in winter 1941/42 are shown in Fig. 4. The results show that use of Lebedev's formula gives values that are slightly too small. For this reason TOPP [9] increased the index 0.62 to 0.64.

For a simple case of vertical static growth of ice MICHEL [6] gives the following formula for calculating the thickness of the existing solid ice:

$$\frac{K_i t_i\, d\tau}{h_i} = \frac{K_s(t_s - t_a)\, d\tau}{h_s} = \varphi_i L\, dh_i \tag{3}$$

where K_i = coefficient of thermal conductivity of that ice
K_s = coefficient of thermal conductivity of snow
φ_i = density of solid ice
L = latent heat of fusion of the ice
t_a = air temperature and temperature of the top surface ice
t_s = temperature of snow

The Michel's equation leads to:

$$\frac{dh}{d\tau} = \frac{1}{\varphi_i L} \quad \frac{1}{h_i/K_i + h_s/K_s} \quad \frac{dS}{d\tau} \tag{4}$$

As Michel pointed out, the above formula can be applied to regions as on the Baltic Sea, where snow accumulations are comparatively small, and where no white ice is formed. The values obtained for the thicknesses of using Michel's formula are given in Fig. 4. The values are sligthly too great at the beginning of the winter.

In his study of the ice thickness observations carried out at Ajos in the winter of 1970/71, Uusitalo [10] states that heat can also be transported to areas below the ice by advection, *i.e.* by horizontal currents. Uusitalo has developed the ice thickness formula into the form:

$$h_i^{(n+1)} = h_i^{(n)} + \int_{\tau_n}^{\tau_{n+1}} (\frac{a}{h} - b)\, d\tau \tag{5}$$

where b is a correction term

The value b has been determined by an iteration method to give ice thickness values measured. Actually b means the heat flow from the water to ice or the amount of ice to be melted from the bottom side. The correction term has been calculated using this method for Röyttä in winter 1941/42 and presented in Fig. 7. The figure also shows the values for Ajos in winter 1970/71 calculated by Uusitalo.

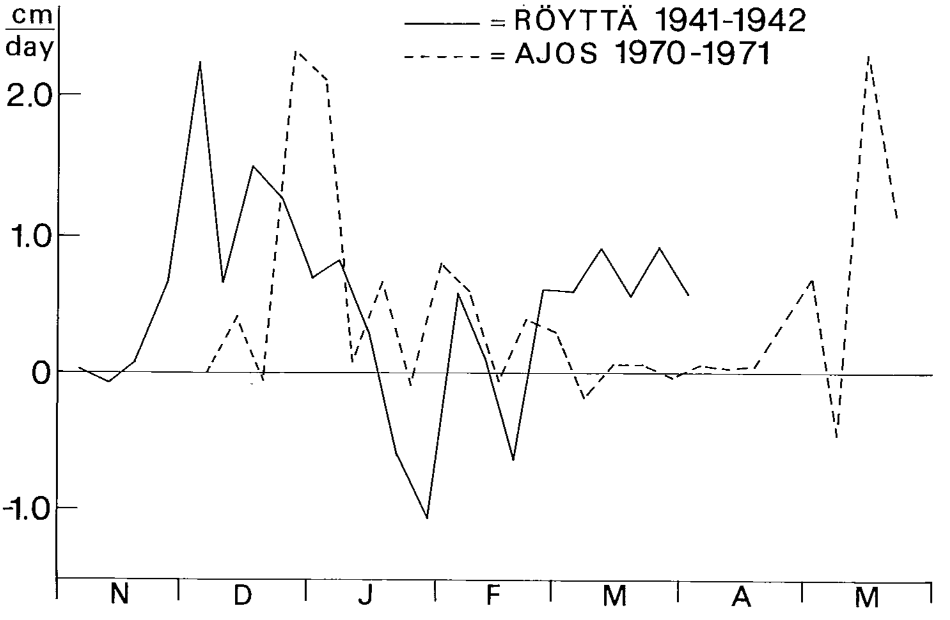

Fig. 7. Calculated heat flow from water to ice or the amount of ice to be melted from bottom side at Röyttä in Tornio during the winter 1941/42. The values calculated by UUSITALO [10] at Ajos in Kemi during the winter 1970/71 are included (dashed line).

As can be seen from Fig. 7, there was a considerable deviation in heat flux for a period of the first month. Taking into account the fact that during this month the open sea of the Bay of Bothnia is still free from ice and that the surface water temperature exeeds 1 °C (GRÖNVALL and PALOSUO, [1]), it is clear that warmer water can flow from this area by advection under the ice. In calculating the thicknesses of ice along the coastal waters of the Baltic Sea this advection term has to be taken into account.

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