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The Structure and Thickness of Lake Pääjärvi Ice

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Abstract

Lake Pääjärvi in southern Finland freezes over every winter and the ice cover is static. The structure of the ice in the lake has been mapped in 1993–1999. The ice thickness ranged from 31 to 70 cm, and the ice sheet consisted of two layers: columnar or macro grained congelation ice and fine grained snow-ice. The snow-ice portion was 10–43 %. The average thicknesses were: 46 cm for total ice, 12 cm for snow-ice and 9 cm for snow. The maximum annual ice thickness showed rather weakly increasing level with decreasing mean winter air temperature. The grain size of snow-ice was typically 1–5 mm with maximum 8–9 mm. The congelation ice showed large macrocrystals, some columnar, with dimensions from 2 cm to more than 10 cm, columns were 2–4 cm in diameter and more than 10 cm in height. Prior to the snow-ice formation the snow layer was compacted in slushing to the fraction of about 2/3. The ice meltwater had the following properties: the conductivity (at 25 °C) was 7–18 µS/cm, pH was 6.1–7.3, and the contents of soluble and suspended matter were 8–18 mg/l and 1.0–2.5 mg/l, respectively. The conductivity and soluble matter contents were 10–20 % of that of the lake water.

Key words: Lake ice, structure, snow-ice, thickness, impurities

1. Introduction

The ice season lasts 5–7 months in Finnish lakes, from November/December to May, and the maximum annual ice thickness ranges from 20 to 100 cm. These lakes have a static ice cover because of the large number and density of islands. The fetches are limited (less than about 10 km) for the wind to build up forces to break the ice and form ridges. Rarely, however, small wind-driven ridges have been observed and (e.g., *Alestalo and Häikiö*, 1979) very small ridges resulting from thermal stresses. A static ice sheet stores the winter history by its layering and growth.

The ice in Finnish lakes is routinely mapped for its thickness but about the structure of the ice sheet only very little information exists (e.g., *Palosuo*, 1965). And in general, long term records for lake ice structure are quite rare. *Gow and Govoni* (1983) presented time series data for several New England lakes. Even less data are available of the impurities (gas bubbles, liquid inclusions and sediments) within the ice.

Lake Pääjärvi is a small oligo-mesotrophic lake in southern Finland (at 61°03'N, 25°10'E). The surface area is 13.4 km^2 and the mean depth is 15.3 m. In winter after ice formation this lake becomes a quiet water body where turbulence and circulation are weak. Observations of modest ridging exist from the past but in general the ice cover is known to be static. Regional lake ice statistics in Finland for the period 1961–1990 show that in the district at Pääjärvi on average the lakes freeze over on 30 November and the ice breaks up on the 5th of May (*Kuusisto*, 1994). The annual maximum ice thickness is achieved in mid-March and is on average 50 cm, with standard deviation 10 cm (*Kuusisto*, 1994). The long-term ice climatology of Lake Pääjärvi is described by *Kärkäs* (2000) showing no significant changes during the 1900s.

Since 1993 the field exercise of the Geophysics of Snow and Ice course of the Department of Geophysics, University of Helsinki has been arranged in Lammi Biological Station at Lake Pääjärvi. As a part of this exercise an ice sample has been taken from the lake and analysed for its crystal structure in a cold room. Since 1996 also impurities within the ice sheet have been mapped in a parallel study (*Leppäranta et al*., 1998). The seven years long time series of the structure of Lake Pääjärvi ice available from consecutive courses is presented below. This is the first such time series from the lakes in Finland.

2. *Material and methods*

The field exercise has been arranged every winter in mid-March when the ice thickness is close to its seasonal maximum. The ice sample has been taken from the central lake area in 1993 and since 1994 from Pappilanlahti bay at the Lammi Biological Station. The depth is about 10 m at Pappilanlahti site. The sampling was made using an ice drill and an ice saw.

The sample was stored in a plastic bag in a freezer and analyzed in a cold room (–10 °C) later. The analysis techniques are described in *Langway* (1958). A vertical thick section was made and photographed for the general structure and thin sections were then prepared and analysed for the size and shape of the ice crystals. Ice crystals are uniaxial with c-axis or the optical axis as the symmetry axis. A thin section is put between crossed polarised sheets. Crystals with c-axis aligned perpendicular to the polarized sheets become black, but due to birefringence other crystals show up in different interference colours. (By turning the section in a universal stage its c-axis orientations can be obtained; but these were not analysed for the present samples.)

The sampling times and the general structure of ice sheet are shown in Table 1. The year 1993 was poor in snow all over the lake, and the site from the central lake showing very low snow-ice portion is thought in that year to rather well correspond to the Pappilanlahti conditions where the sampling was made in later years.

Table 1. The ice samples from Lake Pääjärvi (x – no data).

Year	Day	Total ice cm	Snow-ice cm	Snow cm	Snow g/cm^3	Ice level[1] cm
1993	March 3	31	3	10	0.23	–0.1
1994	March 11	67	13	5	0.25	+3.0
1995	March 24	43	17	7	x	+2.0
1996	March 18	43	5	30	x	–5.0
1997	March 19	35	14	0–2	x[2]	+3.0
1998	March 27	52	10	5	0.33	+4.0
1999	March 23	53	23[3]	6	0.25	+1.0
Mean	March 18	46	12	9	0.27	+1.1
St. dev.	8 days	12	7	10	0.04	3.0

[1]ice surface elevation from the water surface; [2]loose new snow; [3]unfrozen slush layer between 14 and 17 cm from the top.

3. *The structure of ice*

3.1 *Ice formation*

There are two principal vertical layers in a static lake ice sheet (Fig. 1): congelation ice and snow-ice. The congelation ice initiates as freezing of the surface water into a solid ice layer forming so-called primary ice and then grows down into the water (*Shumskii*, 1956). On top snow-ice forms depending on the snowfall and temperature history. In turbulent flow conditions frazil ice may form and attach into the solid ice sheet, and under strong wind or current forcing the ice may break and the resulting blocks pile up into deformed or agglomerate ice. Frazil and agglomerate ice seem to be very rare in Finnish lakes. Sometimes the whole ice layer beneath the primary ice is named as secondary ice (e.g., *Michel and Ramseier*, 1971).

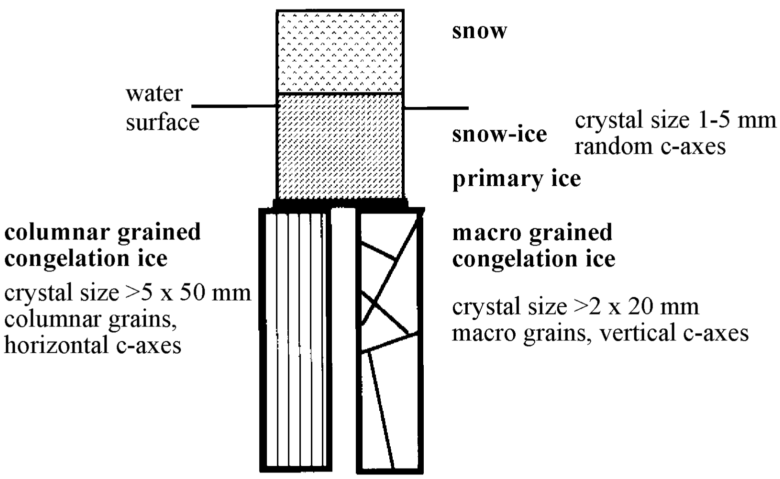


Fig. 1. Lake ice stratigraphy.

The texture of the primary ice depends on the prevailing weather conditions (*Gow*, 1986). So called "quiet freezing" occurs on a calm surface. An ice skim grows horizontally in a supercooled layer and the resulting primary ice layer becomes a few tenths of a millimeter thick. The horizontal crystal size may be large, and the c-axes are predominantly vertical. Freezing begins typically in a cold clear night with large thermal radiation losses from the water body. Disturbed primary ice formation occurs in turbulent water, in windy conditions, or during snowfall. Then the primary ice layer forms of consolidated frazil ice crystals or congealed snow slush and can be much thicker than what results from quiet freezing. The crystal size of ice formed in disturbed conditions is small (1 mm or less) and the orientation of the c-axes is random.

Congelation ice grows further down from the bottom of the ice sheet parallel to the heat flow, i.e. perpendicular to the bottom surface. Its texture is controlled by the primary ice (*Gow*, 1986). Freezing starting in calm conditions produces a strong vertical c-axis orientation which prevails also in the ice growing further down. The crystals are large macrocrystals, some columnar. If the primary ice is initiated in disturbed conditions, the ice growing down becomes columnar grained with c-axes turning horizontal.

Snow-ice forms due to flooding of ice, melt-freeze cycles, or from liquid precipitation on snow cover. For the flooding condition, the ice surface elevation from the water level, h_w, is given by the Archimedes' law as

$$h_w = \left(1 - \frac{\rho_i}{\rho_w}\right) h_i - \left(\frac{\rho_s}{\rho_w}\right) h_s \tag{1}$$

where h stands for thickness and ρ for density, and the subscripts s, w and i are, respectively, for snow, water and ice. The ice level gets down as more snow accumulates. If the weight of the snow is enough, the ice is forced beneath the water surface level. If cracks appear, flooding occurs through them and slush forms which may further freeze into snow-ice; but, however, the ice may bear the snow load long time and then a strong flooding would be observed when making a drillhole. The flooding condition is, from Eq. (1), $h_s \geq \gamma h_i$ where $\gamma = (\rho_w - \rho_i)/\rho_s$. Thus if $\rho_w - \rho_i = 0.1$ g/cm^3 and $\rho_s = 0.3$ g/cm^3, the snow thickness needs to be at least $\gamma = 1/3$ of the ice thickness for the flooding to occur.

In early spring additional snow-ice forms due to the melt-freeze cycles where snow melts in daytime and the mixture of meltwater and snow freezes in night-time. The resulting snow-ice growth is less than $(\rho_s/\rho_I) \times h_s \approx h_s/3$. Also liquid precipitation may initiate the slush formation. Snow-ice y density of snow was 0.23–0.33 g/cm^3. The thickness of snow-ice was 10–43 % of the total ice thickness. The ice surface was within 5 cm from the water surface; only in one case (1996) there was a thick slush layer at the time of the sampling the ice surface being 5 cm beneath the water surface. Taking the ice density as 0.91 g/cm^3 results in that the ice levels are lower than the Archimedes law predicts. The discrepancy is due to the weight of the students at the site.

3.2 The structure of the ice samples

Examples of the vertical cross-sections of the crystal structure are shown in Fig. 2. A brief description is listed below.

1993: The core was 31 cm thick. The top 3 cm was coarse grained snow-ice. The grain size was 2–9 mm, typically about 4 mm. There were a lot of air bubbles; their maximum diameter was 5 mm and they were mostly rounded, large bubbles semirounded. Probably there was surface ice at the bottom of the snow-ice layer. The rest of the ice sheet was columnar grained congelation ice. The columnar ice layer was clear ice, only at depth 16 cm there was a weak bubble layer. On the top there were a few grains of 2–4 cm size, but further down the lengths of the columns were more than 10 cm and their horizontal size grew from 2 to 3 cm with depth. In the lower layer a large frozen crack was observed.

1994: The core was 67 cm. Snow-ice thickness was 13 cm; the grain size was 2–8 mm in the top 5 cm, less than 2 mm in the next 3-cm layer, and 2–6 mm in the rest 5 cm. The boundary between the fine-grained layer and the lower layer was sharp. A zone of large crystals began directly under the snow-ice layer. The grain dimensions were from 2 cm to more than 10 cm and increasing with depth.

1995: The core was 43 cm. The snow-ice portion was 17 cm with a layered sub-structure. The crystal size was 2–5 mm in the top 3 cm, less than 1 mm from 3 to 11 cm from the top, and 1–6 mm in the bottommost 6 cm; at 8–9 cm from the top there were a few small columnar grains. This sub-layering was not totally horizontal. The congelation ice layer was 26 cm thick and consisted of large crystals, the dimensions were from 1 cm to 5–10 cm. Several frozen cracks were found from the congelation ice.

1996: The core was 43 cm. On top there was 5 cm thick layer of bubbly snow-ice and the rest was clear congelation ice. The ice sample broke in the contact of snow and congelation ice during the analysis. The crystal size was 1–4 mm in the snow-ice layer. The congelation ice consisted of large crystals, dimensions from 2 cm to more than 10 cm, with frozen cracks occurring. In the upper part the geometry of the crystals was columnar.

1997: The core was 35 cm. The snow-ice layer was 14 cm, and the grain size was 1–4 mm. On the top of snow-ice (0–6 cm) there were horizontal bubble layers with the bubble diameter 5 mm, and below this large bubble layer there was a fine bubble layer. Then there was a sudden transition into the layer of macrograins and columnar grains. The size of the columns was 1–2 cm in horizontal and more than 5 cm in vertical.

1998: The core was 52 cm. The snow-ice layer was 10 cm, and the grain size was 2–4 mm. There was a sudden transition into the layer of macrograins and columnar grains. The size of the columns is 1–2 cm in horizontal and more than 10 cm in vertical.

1999: The core was 53 cm. Unfortunately the sample was accidentally melted; the stratigraphy had been documented at the sampling site but no results exist for the crystal structure. The snow-ice layer was thicker than in the previous years, 23 cm, and consisted of a 14 cm thick upper layer, 3 cm unfrozen slush, and then 6 cm bottom layer. On the basis of the weather history, a major slush formation event had occurred about four weeks earlier, and from this slushing still there was still a 3-cm layer left.

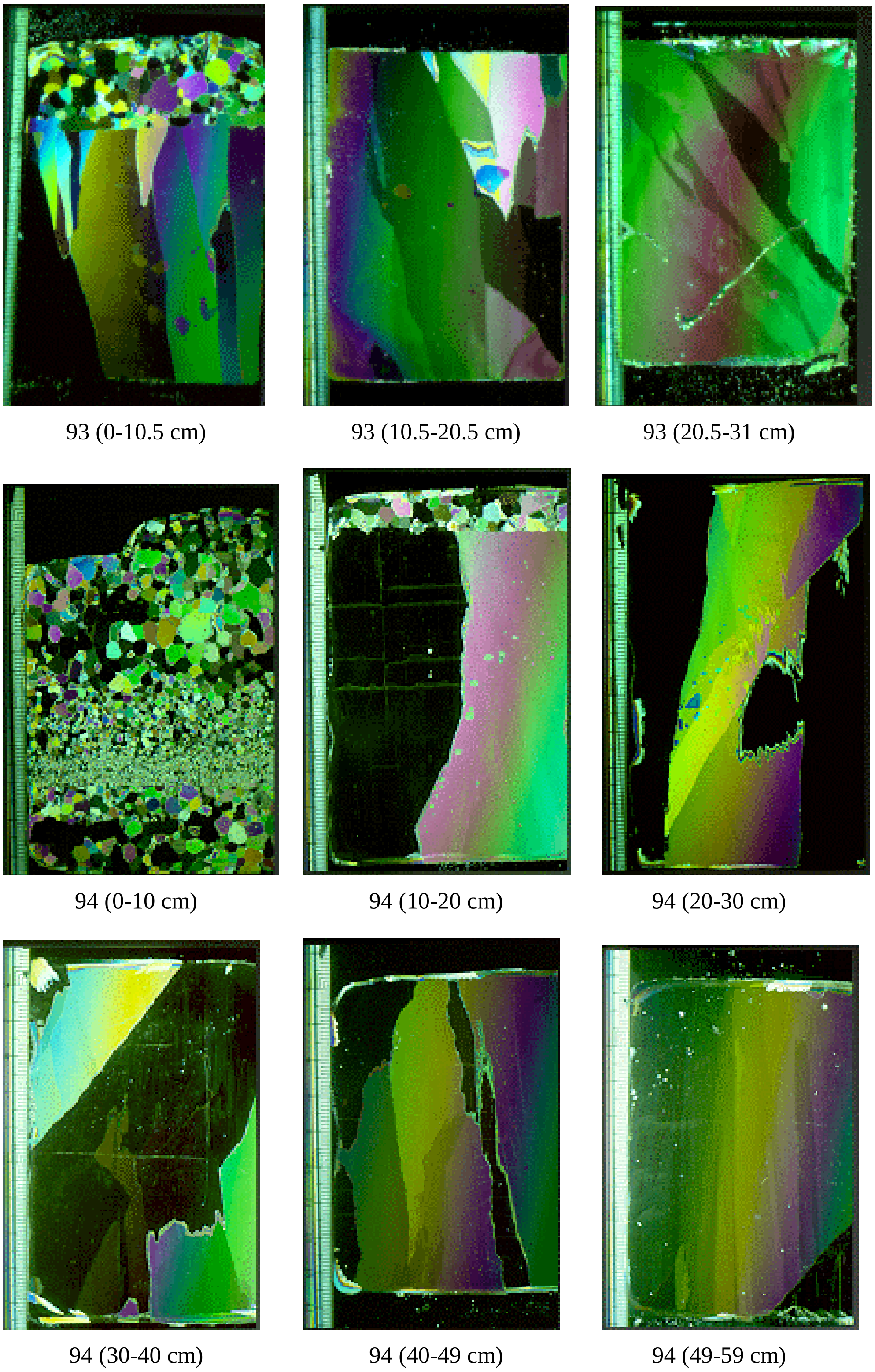
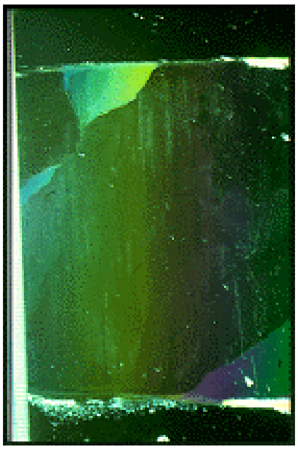
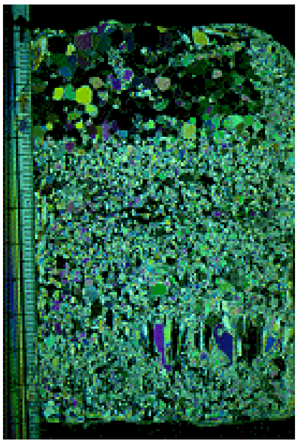
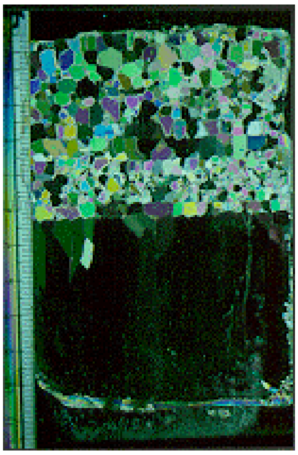
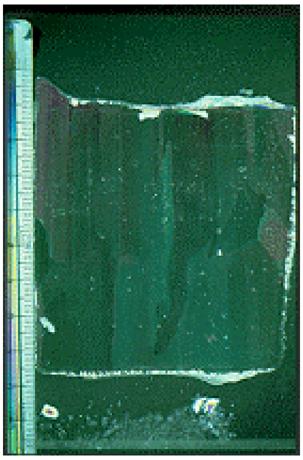


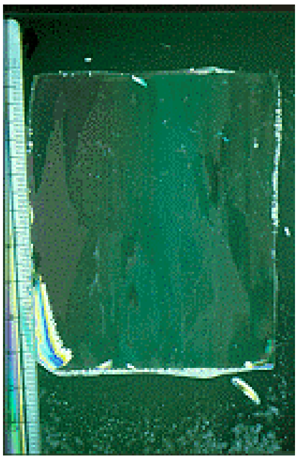
Fig. 2a. Examples of the vertical cross-sections of the crystal structure of Lake Pääjärvi ice. The tic spacing is 1 mm in the scale. Notation 93 (0-10.5 cm): year 1993, section of depth 0-10.5 cm from the surface. (Continues on next page.)


94 (59-67 cm)


95 (0-11 cm)


95 (11-22 cm)


95 (22-29 cm)


95 (29-37 cm)

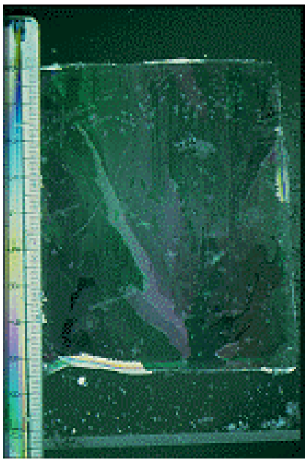
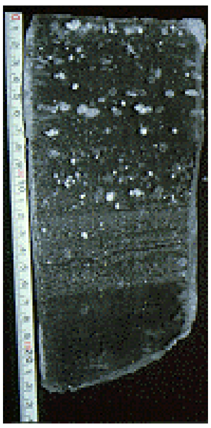

95 (37-46 cm)

Fig. 2a. Examples of the vertical cross-sections of the crystal structure of Lake Pääjärvi ice. The tic spacing is 1 mm in the scale. Notation 93 (0-10.5 cm): year 1993, section of depth 0-10.5 cm from the surface. (Continuation from previous page.)


95 (0-22 cm)

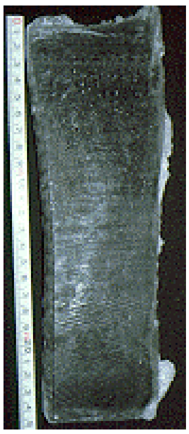

95 (22-46 cm)

Fig. 2b. Thick section in 1995 photographed in normal light. The depth is given in the parenthesis.

Thus the samples consisted of two main layers, granular snow-ice layer on top and lower congelation ice layer with their thicknesses as shown in Table 1. The primary ice layer was likely so thin (less than about 1 mm) that it was not identifiable in the vertical sections; also it had possibly suffered from surface melting. The top 3–23 cm or 10–43 % of the ice sheet was opaque consisting of the snow-ice layer, and the grain size was typically 1–5 mm with maximum 8–9 mm. In one case there was an internal slush layer within the snow-ice layer.

This structure is characteristic to an ice sheet where the primary ice layer forms under quiet freezing conditions (*Michel and Ramseier*, 1971; *Gow*, 1986), in *Michel and Ramseier* (1971) classification "S1 ice". The orientation of the crystal c-axes was not determined but they should be vertical in S1 ice. The size of the crystals was from 2 cm to more than 10 cm, columns were 2–4 cm in diameter and more than 10 cm in height. Frozen cracks were found. No evidence of frazil ice appeared. In quiet initial freezing conditions frazil ice does not form, and as the under-ice lake circulation is known to be very weak here it is unlikely that frazil ice would form after the lake has become ice-covered.

The snow-ice problem can be examined by simple budget analysis. First, there is the following balance condition for the snow volume

$$h_s + \beta h_{si} = H_s \tag{2}$$

where β is a coefficient describing how snow is compressed in the transformation into snow-ice, h_{si} is the thickness of snow-ice, and H_s is the representative thickness of snow cover that would result without the snow-ice formation. In the Pääjärvi data we have the mean thicknesses of snow and snow-ice equal to 9 and 12 cm, respectively, while the mean snow thickness in open land region is in the same period about 30 cm. This gives the estimate $\beta = 1.75$.

A second budget condition results for the thicknesses of normal lake ice (h_{ni}), snow-ice, and snow accumulation in that Archimedes' law tells how much it is possible to form snow-ice by flooding (which is normally the main cause)

$$\gamma\, h_{ni} + (\gamma+\beta)h_{si} = H_s \tag{3}$$

Thus the thicknesses of normal lake ice and snow-ice are not independent but develop together depending on the winter weather history. If $\rho_w - \rho_i = 0.09$ g/cm^3 and $\rho_s = 0.27$ g/cm^3, $\gamma = 1/3$ and an estimate of $\beta = 1.23$ for Lake Pääjärvi is obtained. Fig. 3 illustrates possible proportions of snow-ice and normal lake ice based on the condition (3).

Eqs. (2) and (3) provide two independent estimates of β but they are sensitive to the representative snow thickness H_s; combining them, a rough estimate of $\beta \approx 1.5$ is obtained. This means that in slush formation after a flooding event the flooded snow layer is compressed down to the fraction of $\beta^{-1} \approx 2/3$ of its original thickness. The slush then consists of water and snow the snow fraction being $(1+\beta^{-1})\times \rho_s/\rho_w \approx 0.45$ for $\rho_s \approx$

0.27 g/cm^3. The quantity β has a major importance in thermodynamic modelling of lake ice growth (*Leppäranta*, 1983).

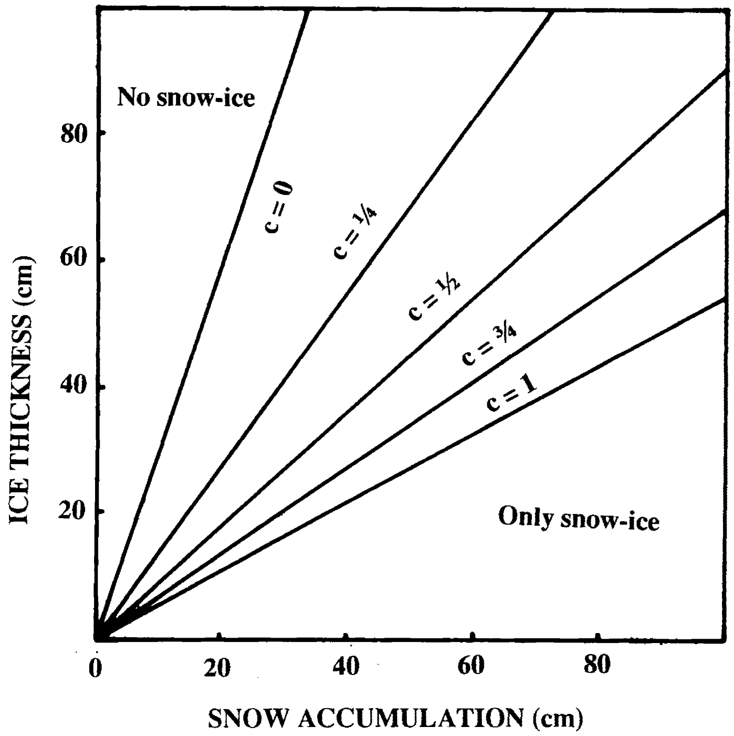


Fig. 3. Possible proportions of normal ice and snow-ice for different ice thickness and snow accumulation cases assuming isostatic balance to hold; c is the ratio of the snow-ice thickness to the total ice thickness.

3.3 Ice impurities

Since 1996 the impurities within the ice have been examined from the meltwater of ice samples in several lakes in Finland (*Leppäranta et al.*, 1998). The Lake Pääjärvi results are shown in Table 2 for the whole ice sheet. The mean conductivity (at 25 °C) was 14 µS/cm, which is 13 % of the conductivity of the lake water. The open season conductivity is in the surface water layer about 90 µS/cm (*Hakala and Arvola*, 1994). Soluble matter was in ice 18 mg/l in 1996 and 1997, 17 mg/l in 1999, and only 8 mg/l in 1998. In the ice suspended matter was 1.0–2.5 mg/l, less than in the water or snow, and the organic proportion varied largely. The snow data from 1996 show much lower pH and higher contents of soluble and suspended matter as compared with the ice data.

In the research programme SUVI (Optics of Finnish and Estonian lakes) summer field experiments have been performed since 1994 (*Arst et al.*, 1996), and more recently an extension to include also the winter phase has been under preparation. In March 1996 data were collected during one week also including Lake Pääjärvi; and the ice and water samples were analysed by Ms. Sirje Mäekivi. Fig. 4 presents the resulting vertical distribution of yellow substance, chlorophyll-a, and suspended matter. The ratios between the concentrations in ice and water were 0.05, <0.16, and 0.25 for yellow substance, chlorophyll a, and suspended matter, respectively. The level of yellow substance, which represents the optically active part of the soluble matter, is very low in the ice formed of lake water. This suggests that the separation of dissolved matter is strong in lake ice growth. Suspended matter levels are also much larger in the water than in the ice. Chlorophyll was at largest in the centre of the core while yellow substance and suspended matter were higher in the upper part of the ice sheet; both were much lower in the ice than in the water beneath the ice.

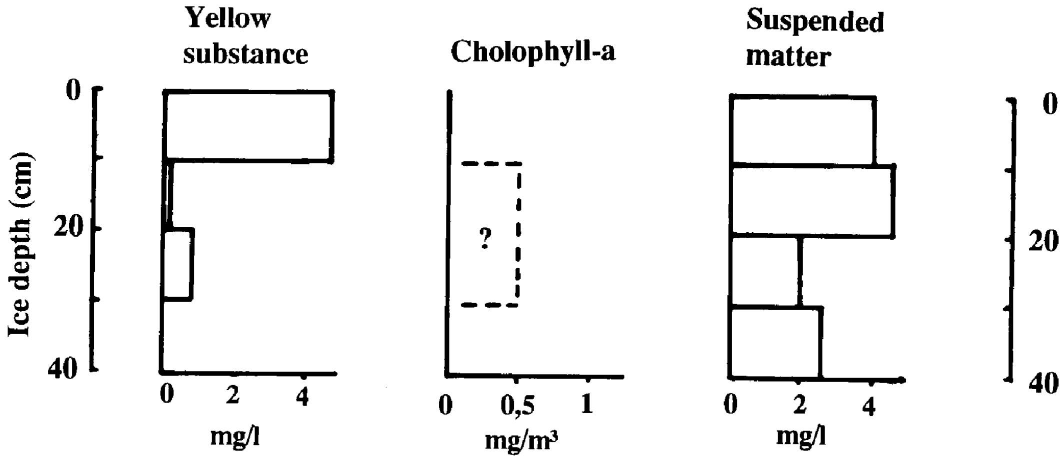


Fig. 4. Yellow substance, chlorophyll-a, and suspended matter in the ice sheet and in the water, 27 March 1996. The chlorophyll a plot is read as "less than 0.5 between 10 and 30 cm and zero elsewhere. The snow-ice thickness was 15 cm in this core. (Ms. Sirje Mäekivi, personal communication.)

Table 2. Properties of the water samples and the meltwater of the ice and snow samples in Lake Pääjärvi; x – no data (*Leppäranta et al.*, 1998).

		Cond µS/cm [25 °C]	Soluble matter (mg/l)	pH	Suspended matter Total (mg/l)	Suspended matter Organic %
1996	Ice	14	18	6.50	1.0	85
	Snow	63	42	3.65	2.6	85
1997	Ice	18	18	6.13	1.6	43
	Water	114	93	6.14	1.6	14
1998	Ice	7	8	x	2.5	8
	Snow	11	11	x	6.6	55
	Water	105	67	x	6.0	40
1999	Ice	16	17	7.25	2.5	56
	Snow	19	20	6.79	1.6	45
	Water	105	57	6.97	3.6	36
Mean	Ice	14	15	6.63	1.9	48
	Snow	31	24	5.22	3.6	62
	Water	108	72	6.56	3.7	30

Both data sets suggest that the soluble impurity level is 5–10 times lower in ice than in water. It is likely that most of the ice impurities result from flooding of the ice and due to atmospheric fallout. This result would be consistent with the present theory of impurity capturing in ice growth (*Weeks*, 1998): the congelation ice growth in lakes very effectively separates soluble matter from the water but in contrast, in sea ice congelation growth the separation is only to about 50 %. This difference is due to different growth regimes as lake ice grows with a planar ice/water interface while in growing sea ice this interface is cellular where impurities become much more easily interlocked. Solving this question more precisely, however, would require a sampling programme with good temporal and vertical resolution.

4. Ice thickness

These seven study years give the thicknesses of the ice samples in the range 31–67 cm while *Kuusisto* (1994) gives the range 30–65 cm for the region around Pääjärvi based on the 30 years 1961–1990. Therefore our maximum ice thickness looks exceptionally high; actually the maximum value measured in 1994 was 70 cm, locating in Pappilanlahti close to the 67-cm ice core. The present average is 46 cm, which is less than the 1961–1990 average of 50 cm.

The average evolution of snow, snow-ice and ice thickness in Lake Pääjärvi is available only for the short period 1971–1978 (Fig. 5). In mid-March the mean thicknesses were, respectively, 10 cm, 8 cm, and 37 cm; the average total ice thickness was thus 45 cm in this period. Compared with our data, the total ice and snow thicknesses are the same but there is more snow-ice in our cases, 12 cm. Fig. 5 also shows that in mid-March the total ice thickness is at its maximum but the snow-ice thickness still grows a few cm which is likely from the slush created by spring melt-freeze cycles and/or liquid precipitation.

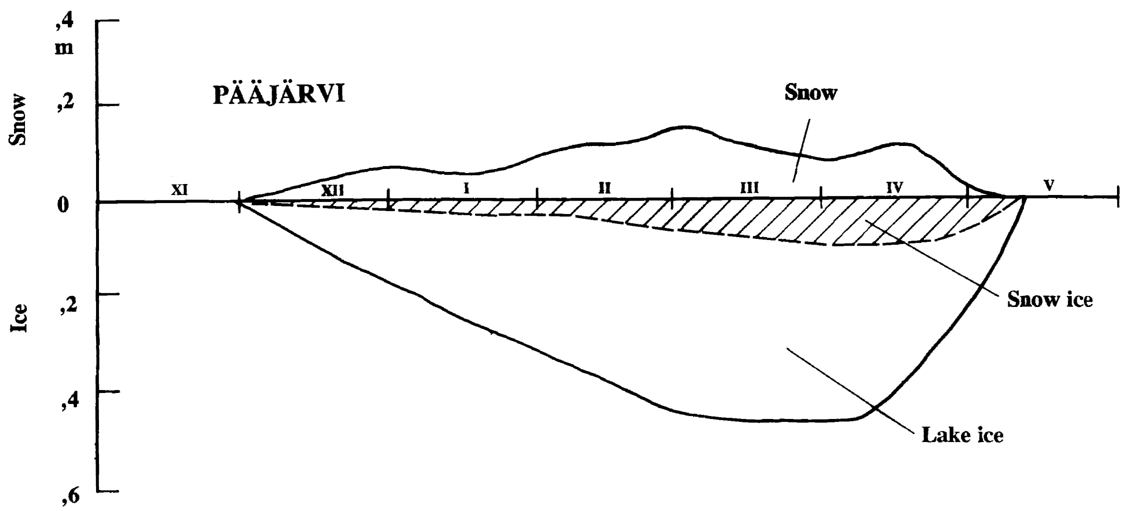


Fig. 5. The average thicknesses of snow, snow-ice and normal lake ice in 1971–1978 in Lake Pääjärvi (*Kuusisto*, 1979).

The initial thickness of the primary ice layer is, as concluded above, very small in Lake Pääjärvi. Thereafter the ice grows as congelation ice at the bottom and as snow-ice at the top. The growth is driven by the conduction of latent heat released in freezing to the atmosphere. For the congelation ice growth, neglecting the thermal inertia, the continuity of the heat flow requires that

$$\rho_i L\, dh_i/dt \;+\; Q_w \;=\; -\kappa_i \times \frac{T_o}{h_i} \;=\; -\kappa_s \times \frac{T_o - T_s}{h_s} \;=\; Q_o \tag{4}$$

where L is the latent heat of freezing, Q_w is the heat flux from the water, κ_i and κ_s are the thermal conductivity of ice and snow, T_o and T_s are the surface temperature of ice and snow, and Q_o is the heat loss to the atmosphere. Note that there must be $0\ ^oC \geq T_o \geq T_s$ in the growth phase. The system of Eqs. (4) can be analytically solved for several special cases (e.g., *Leppäranta*, 1993). In quiet lakes the heat flux from the water can be neglected in the growth season.

A linear form is taken for the surface heat balance: $Q_o = K_o + K_1(T_s - T_a)$ with representative parameter values of $K_o \approx 30$ W/m^2 and $K_1 \approx 15$ W/(^{o}C m^2) for the ice growth season. Take also $h_i = 0$ as the initial condition. Without a snow cover,

$$h_i^2 \;+\; 2(\kappa_i/K_1)\times h_i = \; a^2\, S \tag{5}$$

where $a = [2\, \kappa_i/(\rho_i L)]^{1/2} \approx 3.3$ cm/(^{o}C·day)$^{1/2}$ is the growth factor and $S = \int_o^t \max\{0, -(T_a - K_o/K_1)\}$ is the sum of the degree-days below K_o/K_1. With a snow cover a general solution is not possible; but assuming that the snow and ice thicknesses increase in correlation with each other, $h_s = \lambda h_i$ where λ is a constant, the solution is

$$(1+\lambda)\times h_i^2 \;+\; 2(\kappa_i/\, K_1) \times h_i = \; a^2\, S \tag{6}$$

Semiempirical modifications take a^* instead of a such that $0.5 < a^*/a < 1$. Analytic analysis shows that an effective snow insulation reduces a^*/a to 0.5. Snow-ice formation complicates the ice thickness problem but by analytic analysis it is possible to see that for effective snow-ice production $a^*/a \approx 0.7$ (*Leppäranta*, 1993). Consequently, the thickest ice results when the snow cover is absent or thin.

Table 3 shows the monthly climatology in Lammi which is interesting to compare with the total ice thickness observations. The winter 1992/93 was warm with shallow snow cover, and consequently the thickness was small (31 cm) and the ice was mainly congelation ice. In the following winter the temperature was slightly less than normal with snow accumulation mostly in late winter, and the total ice thickness became large (67 cm). The winter 1994/95 was again warm but with a lot of snow the total ice thickness (43 cm) became larger than in 1993 because of the snow-ice formation. Then the winter 1995/96 was cold with a lot of snow but the total ice thickness remained quite small (43 cm). The heavy snow load forced the ice surface well below the water surface but the ice did not crack (at the sampling site) and the snow-ice thickness remained small. In the winter 1996/97 the almost normal temperature and large snowfall gave total ice thickness of 35 cm which less than one would expect. The snow-ice layer was 14 cm thick and thus very little normal lake ice formed. In the last two winters the total ice thickness was about the same (52–53 cm), a little larger than normal. The winter 1998/99 was colder with much more snowfall resulting in the record snow-ice thickness (23 cm). The conclusion is that the temperature and snowfall, also the timing of snowfall, are the most important factors from the point of view of the total ice thickness.

Table 3. Temperature, precipitation and snow thickness in Lahti in winters 1992/93 to 1998/99 and the normal (1961–1990) reference (*FMI*, 1992–1999). The site is located 30 km east from the Lake Pääjärvi.

		Oct	Nov	Dec	Jan	Feb	Mar	Mean Dec–Feb
1992/93	Ta (deg C)	–0.8	–2.6	–0.2	–2.8	–3.6	–0.9	–2.2
	P (mm)	64	76	19	52	23	27	31
	hs (cm)	3	3	7	5	10	9	
1993/94	Ta (deg C)	2.4	–4.5	–3.9	–5.4	–14.6	–3.4	–8.0
	P (mm)	50	6	58	52	2	49	37
	hs (cm)	0	0	13	19	31	30	
1994/95	Ta (deg C)	3.9	–1.6	–1.6	–4.1	–1.3	–0.3	–2.3
	P (mm)	73	40	50	50	68	43	56
	hs (cm)	0	5	5	17	35	27	
1995/96	Ta (deg C)	7.3	–3.3	–11.0	–7.0	–12.2	–4.2	–10.3
	P (mm)	57	74	26	11	33	24	23
	hs (cm)	0	0	28	40	47	53	
1996/97	Ta (deg C)	6.1	2.7	–6.5	–6.0	–4.8	–1.5	–5.8
	P (mm)	49	136	42	54	41	22	46
	hs (cm)	0	0	5	25	46	0	
1997/98	Ta (deg C)	2.4	–0.6	–4.5	–2.6	–6.6	–5.9	–4.6
	P (mm)	58	33	36	54	49	32	46
	hs (cm)	0	0	8	20	32	20	
1998/99	Ta (deg C)	4.3	–4.4	–3.7	–7.5	–9.0	–2.6	–6.7
	P (mm)	98	26	53	52	67	27	57
	hs (cm)	0	13	13	27	35	53	
Normal	Ta (deg C)	4.5	–0.7	–5.5	–8.4	–8.2	–3.6	–7.4
	P (mm)	58	59	54	43	31	33	43
	hs (cm)	0	2	14	29	41	40	

Comparison between the mean winter temperature T_m and the maximum annual ice thickness h is shown in Fig. 6. In the first approximation, based on Eqs. (5–6), one has a linear form $h^2 \approx \alpha + \beta T_m$ where the coefficients α and β depend on the snow accumulation, air-sea heat exchange characteristics, and air temperature statistics (i.e. how to estimate S from T_m). The correlation between h and T_m is here rather low, 0.43, and the regression parameter estimates are α = 1277 cm^2 and β = 174.11 cm^2/°C. Taking 100 days as the length of the winter, then β should be of the order of $a^2 \times 100$ day ~ 1100 cm^2/°C in Eq. (5). Thus the maximum ice thickness increases much weaker with the negative mean winter temperature than expected from the simple analytic theory.

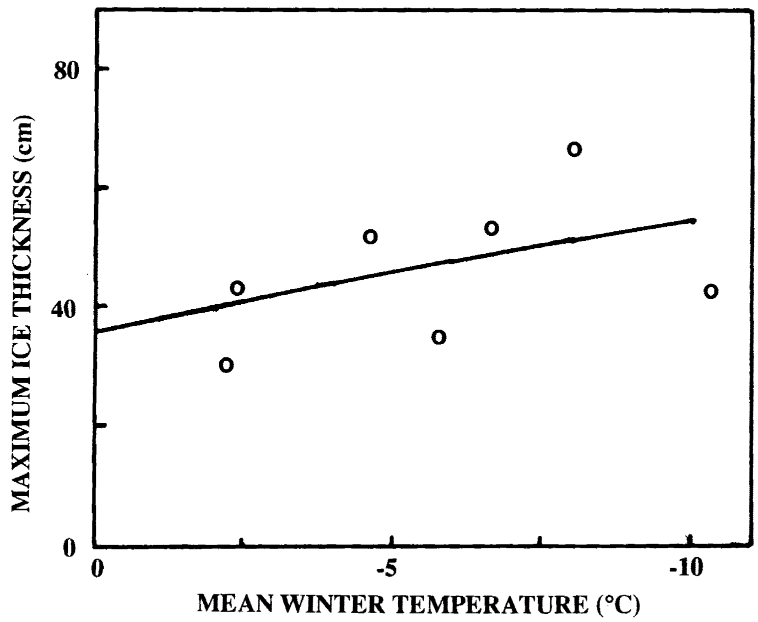


Fig. 6. The ice thickness in Pääjärvi vs. the mean winter temperature. The line shows the linear regression fit for the squared thickness as a function of the mean winter temperature.

5. Conclusions

The structure and thickness of the ice in Lake Pääjärvi in southern Finland has been examined. The sampling has been made as a part of the field exercise of a Geophysics of Snow and Ice course in 1993–1999. The seven years long time series of Lake Pääjärvi ice available from consecutive courses has been presented.

The ice observations were made in mid-March. The ice cover is static and the thickness of the ice cores ranged from 31 to 67 cm. The ice sheet consisted of columnar grained or macro grained congelation ice and granular snow-ice; the snow-ice portion was 10–43 %. The average thicknesses were: 46 cm for total ice, 12 cm for snow-ice and 9 cm for snow; the average snow density was 0.27 g/cm^3. The grain size of snow-ice was typically 1–5 mm with maximum 8–9 mm. The congelation ice showed large macrocrystals, some columnar, with dimensions from 2 cm to more than 10 cm, columns were 2–4 cm in diameter and more than 10 cm in height.

In snow to slush transformation and further snow-ice growth the original snow portion was compressed to the fraction of 2/3. This means that snow-ice contains 40 % original snow and 60 % water that was mixed with the snow, The ice meltwater was analysed: the conductivity (at 25 ^{o}C) was 7–18 µS/cm, which is about 10 % of the conductivity of the lake water, pH was 6.1–7.3, and the contents of soluble and suspended matter were 8–18 mg/l and 1.0–2.5 mg/l, respectively.

The temperature and snowfall, also the timing of snowfall, were the most important factors from the point of view of the total ice thickness. The overall maximum ice thickness of 70 cm was observed in the study region which is exceptionally high in comparison with the existing long-term statistics. The maximum annual ice thickness showed rather weakly increasing level with decreasing mean winter air temperature.

Winter studies are presently increasing in Lake Pääjärvi. In particular the Finnish-Estonian lake optics program SUVI (*Arst et al*., 1996) is extending from summer to examine the all-year cycle in the quality and optical properties of water. In a European lake project REFLECT (Response of European Fresh Water Lakes to Environmental Climate Change) the annual limnological cycle of lakes is examined which also includes the ice season in northern and mountain regions.

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