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The Ice Season of Lake Pääjärvi in Southern Finland

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Abstract

Wintertime observations in Lake Pääjärvi have been made since the beginning of the 20th century. In this study the existing ice data has been collected and analysed. Long time series are needed to investigate the correlation between the weather patterns and ice season and further to study that relationship with mathematical models. For studying the climatic changes, ice records spanning the last few decades are extremely valuable and their value will only increase in the future. The number of observations from Lake Pääjärvi have varied from year to year and the longest continuous series covers about forty years. On average the lake has frozen on December 13th and the break-up has occurred on May 5th. The mean ice season in Lake Pääjärvi has been 144 days and the mean maximum ice thickness 50 cm.

Key words: Lake Pääjärvi, ice season, ice stratification

1. Introduction

Since the 19th century the Finnish Environment Institute and its predecessors have made a lot of observation of ice conditions in Finland. The oldest observations concern freeze-up and break-up dates. The longest record is from Lake Kallavesi where freeze-up and break-up have been observed since autumn 1833. *Laasanen* (1982) has analysed the ice records of 19 Finnish lakes. Between 1960–1979 the dates of the final freeze-up varied from October 25th in north Finland to November 30th in the southern parts of Finland and dates of the final break-up varied from April 30th to June 15th. In some Finnish lakes the ice thickness has been measured regularly since 1910. Between 1961–1990 the mean annual maximum ice thickness in Finnish lakes was 55.5 cm, *Kuusisto* (1994).

Ice dates have been used as climatic indicators. The lake freeze-up and break-up dates are highly sensitive to temperature variations and respond rapidly to warming. In the North American Great Lakes there is a statistically significant indications that the end of the ice season has come increasingly early at a number of locations, *Hanson* (1992). According to *Ruosteenoja* (1986) the dates of break-up correlate well with the springtime mean air temperatures. In Finland spring nowadays begins on average about 9–10 days earlier than in the 19th century. The correlation between air temperature and break-up date is also dependent on the latitude and distance from the coast. Maritime flow influences the temperature in southern Finland positively from September to April and negatively for rest of the year, *Laaksonen* (1977).

In the freeze-up case the November monthly mean is most highly correlated with the southern Finnish lake freeze-up dates. The October 15th to November 15th monthly mean is most highly correlated with the northern Finnish lake freeze-up dates. The southern Finnish lakes are highly correlated with April mean temperatures, while the northern lakes are more highly correlated with the monthly mean temperature in May, *Palecki and Barry* (1986). In addition to mean air temperature also synoptic conditions like precipitation, radiation, cloud cover, wind speed and wind direction affect the final stages of freeze-up and break-up. Lake ice thickness is not a good indicator of climatic variations because it is a complicated function of snowfall and temperature patterns, *Kuusisto* (1994).

Lake Pääjärvi is located in southern Finland (61°04’ N, 25°08’ E) and it is part of the Kokemäenjoki river system. The Pääjärvi area lies between the first and the second Salpausselkä ridges. A total of 25 small streams and drains flow into the lake. It is one of the deepest lakes in Finland with a maximum depth of 87 m (Figure 1). An average depth is 14.4 m and a surface area of 13.5 km^2. It is at an altitude of 103 m above sea level. The mean annual air temperature between 1964–1994 was 3.6 °C. The warmest month was July (16.0 °C) and the coldest was January (–8.5 °C) (based on information from *http://www.helsinki.fi/ml/lammi/*). On average the snow cover appears on December 7th and melts away on April 23rd. The annual precipitation is 610 mm and 37% of it falls between December–May, *Lemmelä* (1971). The lake is frozen for five months of the year.

Ice observations have been made in Lake Pääjärvi from the beginning of the 20th century. More continuous research started after the Lammi Biological Station was founded near the lakeshore in 1953. The longest data series are from the weather station, which has run continuously since the year 1964. Other observations have been made more irregularly in connection with different projects. However, Lake Pääjärvi has been the subject of several research projects for a long time and some physical processes, like water temperature and meteorological variables, have been well studied. Lake Pääjärvi was the representative area in Finland for the International Hydrological Decade (IHD, 1965–1974), *Lemmelä* (1971). It was also studied in the Finnish Research Programme on Climate Change (SILMU, 1990–1995), *Elo et al.* (1998).

A new international project REFLECT (Response of European Freshwater Lakes to Environmental and Climatic Change) commenced in 1998. REFLECT is studying European lakes situated in three different climatic zones. The main purposes of the project are to study factors that influence the temporal dynamics of plankton in lakes and to make water quality models. Lammi Biological Station and Department of Geophysics of the University of Helsinki are the Finnish members of the project. In Finland the primary site is Lake Pääjärvi. One problem in Finnish lakes compared to those in southern Europe is the ice season. Long time series are needed for lake climatic investigations. The aim of this study is to collect and analyse the historical ice data from Lake Pääjärvi, from 1910–1998.

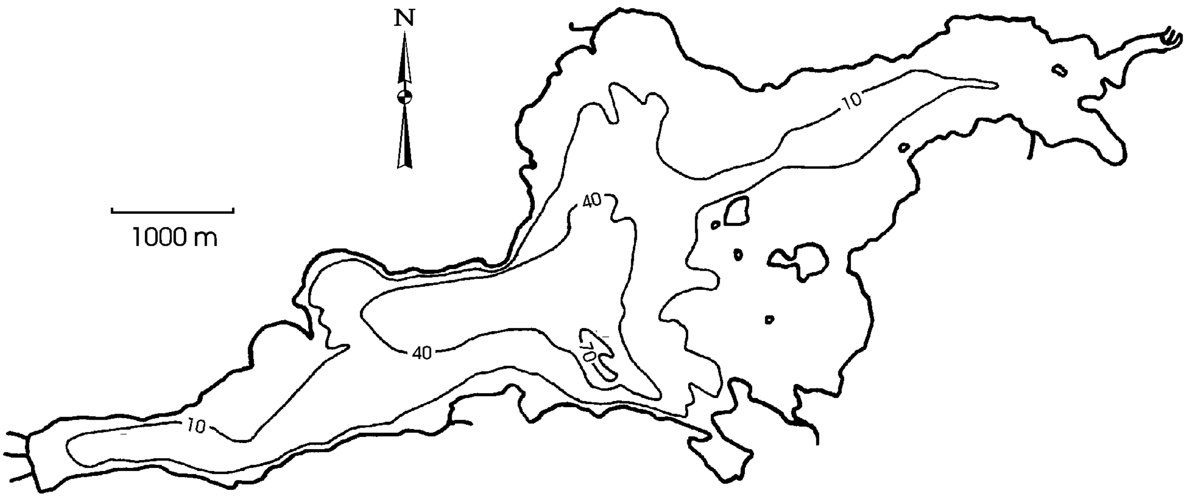

Fig. 1. The topography map of Lake Pääjärvi (contours in meters).

2. Theory

In Finnish lakes the thermal year can be divided into an open water period and an ice cover period. The dividing events are freeze-up and break-up. Ice forms when the air temperature has been continuously negative. Freezing usually occurs on a calm and clear autumn night when water movements are small and heat exchange with the atmosphere is large. In calm conditions crystals grow horizontally at the surface. A uniform ice cover forms when the crystals combine with other and after that the ice thickness starts to increase.

Cooling of water in the autumn makes the stratification of the lakes more stable after passing the density maximum of water (4°C). The shores of lakes freeze earlier than the middle. After the summer the heat storage in deep waters is greater than in shallow waters. The freeze-up is also highly dependent on flow and wind conditions. In Finnish lakes the ice cover is usually horizontally quite uniform because of a weak wintertime circulation under the ice cover. The ice cover is a very good insulator and the snow cover above makes it even better. A solid ice cover effectively blocks energy exchange between the water and the atmosphere. In Finnish lakes, November is a very important month for the increase of ice-covered areas, *Kuusisto* (1994).

According to Stefan's law the thickness of snow free ice h_I (in cm) can be estimated as follows, *Stefan* (1891)

$$h_i^2(t) = h_{i0}^2 + a^2 S(t) \tag{1}$$

where S is the sum of negative degree-days after the primary ice formation, h_{i0} a start up value for ice thickness and a the growth factor:

$$a = (\frac{2\kappa_i}{\rho_i L})^{\frac{1}{2}} \tag{2}$$

where κ_I is the thermal conductivity of ice, ρ_I the ice density and L the latent heat of the fusion of ice. The used value for a is 3.3 [cm/(°C×day)$^{1/2}$].

Usually there are three main vertical layers in the ice cover. Primary ice is the first freezing ice layer. Snow-ice forms above the primary ice from slush. Columnar congelation ice grows downwards underneath the primary ice. The grain size of the columnar congelation ice gets larger as the ice gets thicker. On average the mean ice thickness on Finnish lakes increase almost linearly from mid-November to the end of January, *Kuusisto* (1994). The maximum annual ice thickness h_{max} can be estimated from the formula

$$h_{\max} = a\sqrt{S} \tag{3}$$

The snow cover roughly halves the ice growth. Snow has an important role in the ice growth mechanism because of its insulating effect and the formation of snow-ice. If the ice is covered with a thick snow layer early in the winter, the ice remains relatively thin even in the cold winters. If there is only a little snow on the ice a relatively thick ice cover is formed even in only slightly subfreezing temperatures. The average date for the maximum ice thickness is around mid-April in Lapland. In southern Finland this date occurs about one month earlier. After mid-April the melt rate is fast. On average 68% of all lake ice melts within one month, *Kuusisto* (1994). The spring break-up processes are less directly dependent on air temperature, *Palecki and Barry* (1986).

Melting starts from the shore because the land absorbs radiation more effectively than ice. When the snow on the ice has melted the albedo of the ice cover decreases considerably and melting increases. The end of the process is very much dependent on the synoptic conditions. Windy weather greatly increases the mechanical break-up of ice.

3. *Observations*

The available data from the Lake Pääjärvi winter seasons contains seasonal ice characteristics, ice structure, snow conditions and weather observations (Table 1). Only freeze-up and break-up dates exist from the early part of the 20th century. The Finnish Environment Institute and Lammi Biological Station have made most of the observations but Department of Geophysics has also made a few. Meteorological quantities have been recorded daily at Lammi Biological Station since 1964.

Table 1. Observations and observation periods made by the Finnish Environment Institute (E), Department of Geophysics (G) and Lammi Biological Station (L).

OBSERVATION QUANTITIES	DATA AVAILABLE
1) Sediments in the ice (G)	
2) Crystallography of the ice (G)	
3) Ice thickness and snow depth (E)	
4) Ice line measurements (E)	
5) Snow line on the ice (E)	
6) Ice stratification measurements (E)	
7) Freezing and break-up times (E)	
8) Depth of snow in land (L)	
9) Precipitation (L)	
10) Air temperature (L)	
YEARS	1910 1920 1930 → 1960 1970 1980 1990

The longest time series are for ice stratification and ice season measurements made by the Finnish Environment Institute. Ice stratification observations cover measurements of ice thickness, free board, snow depth, snow-ice thickness and snow ice growth. These have been measured twice or three times a month in the ice seasons for 1977–1985, 1989–1991 and 1993–1998. Freeze-up and break-up dates have been recorded between 1910–1930 and 1971–1988. For the period 1910–1930 of freeze-up and break-up dates has been collected from the old water level forms of the Finnish Environment Institute. The forms are nowadays stored in the National Archives. In the winters of 1971–1980 The Finnish Environment Institute made snow depth measurements on the lake ice and in the winter of 1992 ice thickness measurements from January to March. They also has measured ice thickness and snow depth at the same time as they took water quality samples from Lake Pääjärvi (Table 1, item 3). The results were too inexact to be used for further statistical analyses.

In the lake ice observations four types of freeze-up and break-up data types were recorded. The freeze-up data includes the dates of ice formation on the shore, ice cover on the bays, ice within the visible range and the final freeze-up. The break-up data includes the dates of open water on the shore, open water offshore, ice in movements and the final break-up. In this study the dates of the final freeze-up and the final break-up have been used.

Since 1993, Department of Geophysics has made an ice and snowfield study every mid-March in Lake Pääjärvi. Ice thickness and ice stratification have been measured and crystal structure has been analysed later in a cold room. Since 1996 sediment content has also been analysed, *Leppäranta and Kosloff* (1998).

4. Results

The statistics for the freeze-up and break-up dates are shown in Table 2. During the whole period the average ice season length was 144 days with a standard deviation of 24 days, the freeze-up date was December 13th and break-up date was May 5th. A t-test shows that the mean values for freeze-up and break-up dates do not differ significantly between the years 1910–1930 and the years 1971–1988. The break-up date has not been occurred early in the period 1971–1988 than the period 1910–1930. According to *Lemmelä and Kuusisto* (1975) in the inland lake area of Finland, small lakes begin to freeze up at the beginning of November, and towards the end of December all lakes usually have some ice cover. During the period 1951–1970 Lake Päijänne froze up on average on December 15th and Lake Näsijärvi on December 16th. Corresponding values for the northern lakes Oulujärvi and Kilpisjärvi are November 18th and November 11th. Differences in the break-up dates on lakes are considerably smaller than in their freeze-up dates. Large lakes of southern and central Finland were ice-bound on average 140–160 days a year, *Lemmelä and Kuusisto* (1975). Lake Pääjärvi follows the average values of the lakes in southern Finland very well.

Table 2. Ice season statistics. Units are date and day, n=observation winters.

Period	1910–1930 (n=18)	1971–1988 (n=16)	1910–1988 (n=34)
Mean freeze-up	Dec. 15	Dec. 11	Dec. 13
Latest freeze-up	Jan. 28 (1930)	Jan. 29 (1980)	Jan. 29 (1980)
Earliest freeze-up	Nov. 16 (1919)	Nov. 16 (1919)	Nov. 16 (1919)
S.D. freezing	16	15	16
Mean break-up	May 4	May 6	May 5
Earliest break-up	Apr. 14 (1921)	Apr. 14 (1921)	Apr. 14 (1921)
Latest break-up	May 18 (1927)	May 18 (1927)	May 18 (1927)
S.D. break-up	10	6	8
Mean season length	141	147	144
Min. season length	80	104	80
Max. season length	175	169	175
S.D. season length	28	19	24

The duration of the ice season and its variations can be seen in Figure 2.

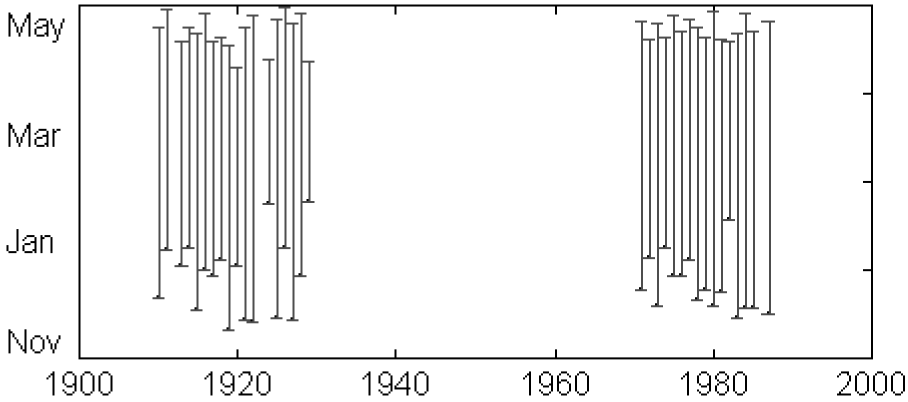

Fig. 2. The duration of the ice season.

In the whole period, 1910–1988, the freezing season lengths are shown in Figure 3. The longest ice season of 175 days was in the winter of 1922–1923. The shortest season of only 80 days was in the winter of 1929–1930.

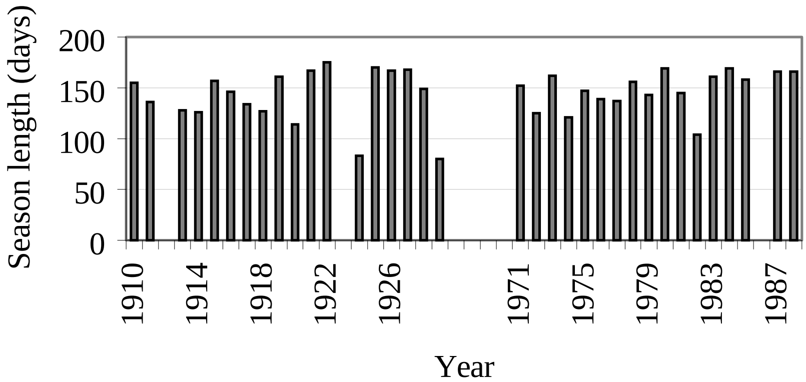

Fig. 3. The season lengths in days.

The correlation between the ice season length and the mean air temperature of December–March was –0.45 which is considered to be weak. The used data covers the years 1971–1988. The correlation between the ice season length and the winter sum of negative freezing degree-days was 0.59. The mean sum of negative degree-days (the frost sum) in that period was 861.4 °C×day. *Palecki and Berry* (1986) found a relationship between November mean air temperature and southern Finland lake freeze-up dates.

The Finnish Environment Institute has made ice structure measurements during the years 1977–1985, 1989–1991 and 1993–1998. Monthly mean values can be seen in Table 3 and Figure 4. The maximum measured ice thickness was 68 cm and the mean maximum ice thickness was 50 cm with a standard deviation of 9 cm. The mean maximum ice thickness was 45–60 cm for the lakes of southern and central Finland. The maximum thickness is usually reached towards the end of March or at the beginning of

April in the lakes of southern and central Finland, *Lemmelä and Kuusisto* (1975). According to *Laasanen* (1982) the mean maximum ice thickness in the period 1960–1980 in Lake Pääjärvi area was 50–55 cm and the mean date of the maximum thickness was between March 15^{th} – March 20^{th}. In Lake Pääjärvi the smallest annual maximum ice thickness (35 cm) has been measured in February 1979. The measured maximum snow-ice thickness was 25 cm and the smallest annual maximum snow-ice thickness was only 7 cm. The maximum ice thickness values, obtained by using Eq. (3), are on average 54 cm bigger than the measured ones. Eq. (3) does not take into account the insulation effect of the snow cover above the ice. The snow cover on the ice has been thickest in February and the maximum in the ice thickness has been in March.

Table 3. Ice stratification statistics from the years 1977–1998 (16 years of data).

Month	Snow (cm)	Snow-ice (cm)	Ice (cm)
Nov.	0	0	0
Dec.	6	2	20
Jan.	12	7	33
Feb.	13	10	42
Mar.	11	12	47
Apr.	2	14	39
May	0	0	0

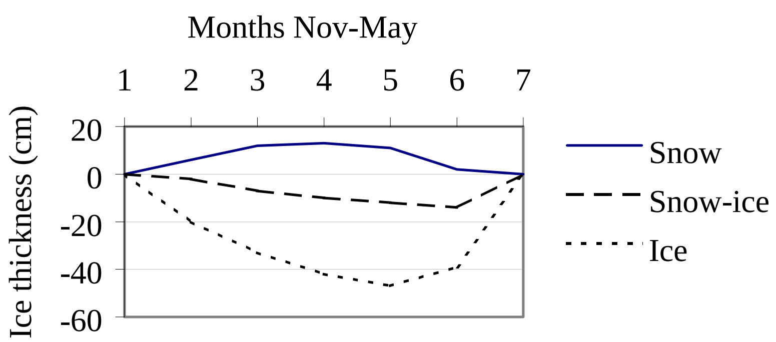

Fig. 4. Ice and snow-ice thicknesses, and snow depth on ice.

The columns in Figure 5 show the ice stratification and snow depth on March 30^{th}. Only the years when all three quantities have been measured are presented. Black ice contains both primary ice and columnar congelation ice. On average there has been 69% of black ice and 31% of snow-ice.

Snow depth has been measured in Lake Pääjärvi every 16^{th} day of January–April between 1971–1980. On land the snow depth has been 2.3 times thicker than on the ice. On the same day the measured snow depth on land was on average 14.5 cm larger than on ice. But on ice we have to take into account the formation of snow-ice. Because of snow-ice the real difference is less than the measured one.

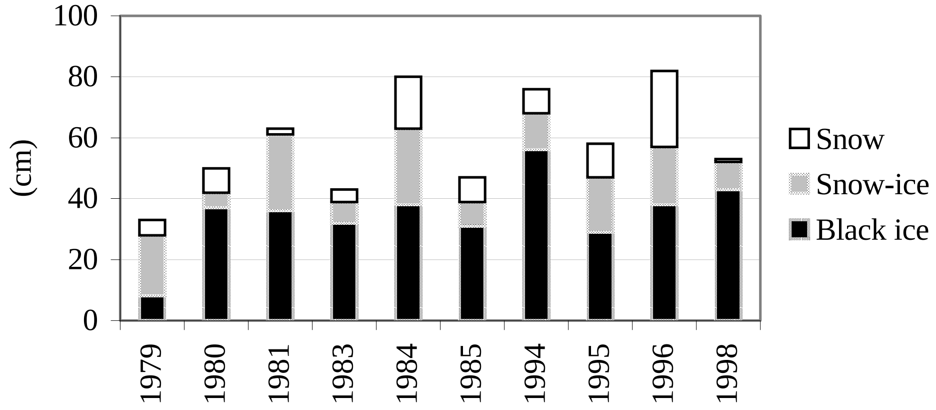

Fig. 5. Ice thickness and snow depth on March 30.

5. *Conclusions*

There is not seen any significant changes in freeze-up and break-up dates between the periods 1910–1930 and 1971–1988 in the Lake Pääjärvi ice records. The spring melting has not started statistically any earlier at the end of the 20th century. The observation record might be too short for major changes to be seen. The correlation between the ice season length and the mean air temperature of December–March was weak. Ice season length seems to be more related to the dominant temperatures before freeze-up and break-up events than the frost sum for the whole season. Lake Pääjärvi is one of the deepest lakes in Finland. Despite its exceptional deepness it is a representative southern Finnish lake. It follows very well the average ice data values which have been obtained previously for the lakes in southern Finland.

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