Long-term modelling of winter ice periods
for morphologically different lakes

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Abstract Winter ice cover can be related to the temperature of air, but morphological and meteorological differences cause large variations. Physically based modelling help their study, as results can be controlled and verified. A lot of data is needed, and in the process liability and interpretation of data are important. In this study long series of data are used to study winter ice coverage of morphologically different lakes in Southern Finland. Physical factors in the vertically resolving lake model, the Probe model, were considered.

The ice model is based on the use of the temperature of air and it is successful in describing regular ice formation and break-up. Suitability for individual lakes could be improved by changing the factors for melting, the wind limit for breaking the ice and the temperature limit for determining ice coverage. Depth delays and mixing increases cooling of water. For freezing date, the differences between lakes are about one month. Ice break-up is strongly determined by air temperature, but the model can help to relate differences to morphology. During warmer winters horizontal variations have more importance; there can also be periods of partial ice-cover. For further study of those the model should be developed; modelling over years in succession is then a necessity.

Keywords Ice model; ice statistics; lake ice

Introduction

The yearly cycle gives natural periodicity also for lakes with typical seasonal conditions, but years can also differ strongly from each other. Natural laws and causal relations use simple sets of explicators in models to describe phenomena and changes explicitly with numbers. In nature changes occur in systems continuously seeking balance. To be usable models should be simple enough, but produce essential features. On the other hand, they should be sensitive enough to describe finer variations that can have important effects. A strongly determining changing variable is the temperature of the air; it regulates many processes and is related to many other variables. Freezing and melting of water are classically used to determine zero temperature, giving accurate information about temperature. That is why freezing and break-up of lake ice can give good information about meteorological conditions over sufficient long periods, even longer than instrumental observations. Several variables affect freezing and break-up, especially for morphologically different lakes: with different depths, area and shapes both inside and above the surface. There can be differences in the climate for relatively close lakes due to local meteorological conditions. The changes in heat stored are affected by the volume and shape of the water body. Differences can be studied statistically, but often that method is limited by the amount of observations available: the differences can be large between lakes. This is most clearly seen in areas having large numbers of different kinds of lakes. Also the reliability of the data is of importance, and relatively large amounts of data are needed, both meteorological and hydrological. In this study these questions are studied in

connection with modelling. Systematic use of the model helps in filling the data and interpreting variations of data quality. Basically the same meteorological data are used in this study for all of the lake applications with basically the same model for each lake. Calibration to each site was found to be essential. The objective was to look for the main effects caused by morphology and those by climate, which also helps in defining the changing climate effects. This can be done by constructing a physically based model, which can be used to analyze the importance of different processes and control and verify the results.

For lakes meteorological variables can have important variations over each lake. The scales involved in these aspects usually differ from those used by meteorological observation systems, which have also suffered from changing conditions and locations. Magnuson *et al.* (2000) have collected a large set of lake ice data, longer than 150 years over the Northern hemisphere. The most homogenous series were selected; they show generally clear signs of a warming climate, including though local differences. Individual lake ice data series have also been successfully related to air temperature series and in that way related to climatological changes (Livingstone 1997). Stewart and Haugen (1990) studied the influence of lake morphometry on ice dates considering many variables. They found for their lake set in New York State that depth is most important after the temperature of air. This has also often been found earlier, e.g. by Simojoki (1940) for Finnish lakes, especially for freezing. Stewart and Haugen (1990) summarize that for Finnish conditions ice break-up has less variability than freezing and that it is more clearly determined by solar radiation and therefore by location. This is based on studies by Lemmelä and Kuusisto (1975) and Laasanen (1982). In Canadian conditions, Stewart and Haugen write that it has been found that there is more variation in ice break-up than freezing, associated with more complicated processes involved, found by, for example, Ashton (1980), but for the small set they were not able to find a clear answer.

Earlier articles (Huttula *et al.* 1992; Elo 1994; Elo *et al.* 1998) describe the PROBE model and its applications. Elo and Vavrus (2000) describe a comparison of the included ice model and the LIMNOS model. Lakes Pääjärvi and Mendota in Wisconsin were modeled with both of the models. Ice dates could be modelled with both of the models and the total ice thickness could be given realistically even without separate snow cover descriptions.

Methods and special questions involved in the approach

Ice data

It is often difficult to find sufficient amount of information about ice data, series of ice formation and break-up for lakes in similar conditions, especially having enough information concerning meteorological conditions. The lakes studied by Stewart and Haugen were situated in a landscape having also relevant altitude variations. Livingstone (1997) found that a mountain landscape had a strong influence on meteorological conditions for lakes situated relatively close to each other. Flow conditions inside lake water vary between lakes and their sub-basins: strong and possibly warmer flows weaken ice cover. Especially, spring flooding can cause breaks and water can rise over ice. Heating is enhanced: once snow has melted the shore land area appears relatively dark, increasing absorbance and warming the air. Also sheltering by the shores, and therefore calmer circumstances, can cause warmer conditions over smaller lakes. In Canada it has been noted that the type of ice and large amounts of snow cause differences in melting order between shores and pelagial area (Adams 1981).

Ice growth

The original formation of ice crystals, their growth and absorption of heat during thawing influence the final ice break-up. The main reason for ice growth is the cold air, which freezes water. Ice remains floating between air and water due to the density difference. For lakes the

conditions during freezing are typically calm. This is well described by, for example, Adams and Graig (1987). Freezing can then occur relatively fast and the c axes of the forming crystals can be oriented horizontally, vertically or both. Ice crystals grow vertically along the heat exchange between water and atmosphere. Impurities remain between crystals, and their concentration and form can affect melting. Even heating of water by light beneath the ice can affect melting and already Simojoki (1940) proposed more analysis of light conditions under ice. The detailed mechanics for ice growth is complicated, as described by Leppäranta (1993). The use of detailed methods would require determining constants used and their time evolution, while local differences can be most important. There are also differences caused by the different composition of water.

Slush ice

Palosuo (1965) discussed another factor that can be of great importance for the ice conditions: slush ice. This is freezing water, which gets over the regular ice formed. It can rise over the ice or be melted or precipitated during mild seasons. Also, fallen snow can form ice, but aging of snow into ice is typically so slow a process that it would take some years and continuously increased pressure for it to be transferred into ice. Large amounts of snow over lake ice can, during the winter, increase the weight of the ice cover so much that water rises over it through available cracks. This can be influenced by flows, changes of water level and involved winds (Simojoki 1966). Some effects included can be relatively strong, e.g. temperature changes can cause cracking of ice. This is often noted over polar oceans where temperature differences are typically larger.

Regular ice is often called black ice due to its opaqueness because it appears very dark due to little reflection. It has rather a small extinction coefficient. Slush ice, and particularly snow, are gray and white and light cannot penetrate thick layers, so slush ice is also called white ice. Impurities in snow increase absorption of light and therefore enhance melting. Typically, at least in Finland, snow melts first and after that ice begins to melt. Slush ice is formed in certain climatic conditions and it is typical for Finland. A little more to the south in Southern Sweden the climate is so mild that lakes don't even always freeze. More slush ice is formed again in the Northern parts of Sweden. Snow cover can vary a lot horizontally, depending on circumstances, especially on sheltering. In principle the surface tends to get smoother when wind can move snow, therefore horizontal depth distribution can in principle be typical for each lake depending on its area and shore forms. Observations can anyhow show small variations in depth of snow over a lake (Simojoki 1940; Kuusisto 1973; Eklund 1998).

Study area

The lakes modelled in this paper are situated in the lake district of Southern Finland, shown in Figure 1. Their shapes and sizes are also presented in the figure, but for the small lakes merely the location can be seen. Table 1 gives the basics of their morphology, area and depth, and also locations. Meteorological data used have been observed and recorded in the town of Jyväskylä, which is situated in the middle of this lake area. This data have been used for all of the lake applications, using assumptions that describe the climate in that relatively small area. Basic differences caused by local variations are taken into account comparing long term averages.

Horizontal variations and morphology

The model is one dimensional and horizontal variations cannot be explicitly treated. Therefore their effects have to be estimated using information about them and their importance regarding the interpretation of ice observations. Horizontal variations depend

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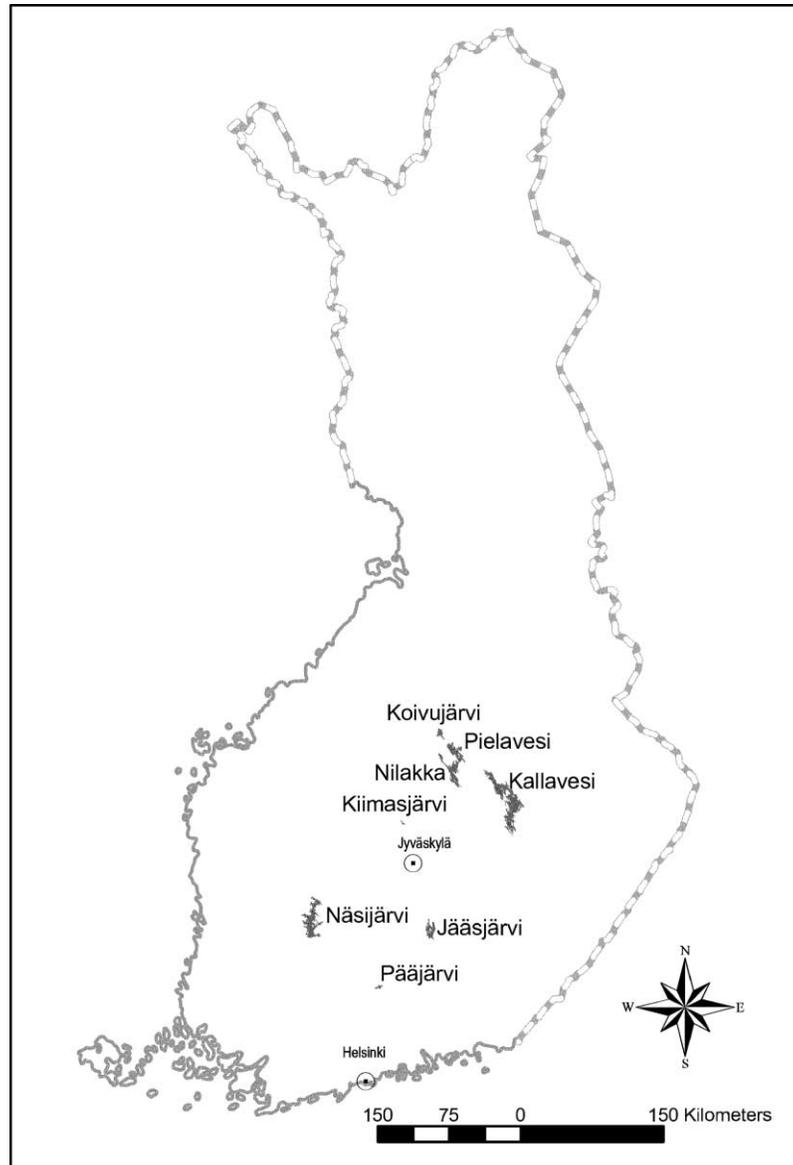
Figure 1 The study lakes. The lakes studied in this article are drawn in their shapes and sizes at their locations on the map of Finland. Two cities, Helsinki and Jyväskylä, are also shown in the figure. Meteorological data used is mainly based on observations and recordings from Jyväskylä. (© Maanmittauslaitos, lupa nro 468/MYY/04)

typically on the rate of the change of water temperature. Shallow shore areas typically freeze and melt first, but during break-up typically horizontal variations are more influenced by the atmosphere: as long as there is ice cover it shields the water surface. Under the water the bottom can release heat, which can intensify melting close to the shores. Currents under ice can have important local effects. Some data of Finnish conditions can be found in Simojoki (1940). In his publication there are average dates for 32 lakes which, according to their locations, are inside the area in this study. This data also includes information about the lakes in this study as described below. There are dates for first freezing (number of years $N = 16$), complete freezing ($N = 22$), first melting ($N = 15$) and complete melting ($N = 21$). These

Table 1 The study lake

Lake	Area (km^2)	Depth (m)	Location
Lake Pääjärvi	13	85	61°04′N, 25°08′E
Lake Koivujärvi	26	16	63°28′N, 26°15′E
Lake Kallavesi	887	71	62°50′N, 27°40′E
sub-basin	41	50	
Lake Jääsjärvi	65	20	61°37′N, 26°08′E
Lake Pielavesi	270	31	63°20′N, 26°32′E
(Nilakka)			(63°08′N, 26°33′E)
Lake Näsijärvi	257	51	61°32′N, 23°45′E
Lake Kiimasjärvi	3.8	19.5	62°37′N, 25°32′E

are not necessarily for the same years and lakes, and the lakes are different in many aspects, but they can indicate what kind of behavior has been present. According to them freezing takes on average 19 days (SD 8 days) and break-up 10 days (SD only 3 days). As the lakes lie close to each other, the air temperature is almost the same, and the clearest effect is caused by the depth: deeper lakes freeze later. Total length of ice cover varies accordingly, but for these lakes it is not seen that smaller lakes would freeze quicker, determined from the first ice to total ice cover. This process is fastest for Lakes Pielavesi and Nilakka, which is a rather large double-lake system, connected by a canal. In Lake Pielavesi freezing is completed in seven days and melting in nine days, while in Lake Nilakka it is nine and five days respectively, and in the connecting canal four and three days. Due to flow conditions freezing can occur faster than melting and strong mixing can decrease horizontal variations in autumn. In spring flow can enhance melting locally. For Lake Vanajavesi the durations are 14 (freezing) and 17 (melting), while for Lake Jääsjärvi 15 and 8 days. The shape of Lake Jääsjärvi is very complicated, which can influence the relatively long time taken for melting.

Effects of climatic variations

There can, of course, also be local differences in climatic conditions, which additionally influence heat intake. In his study, Simojoki (1940) described differences between Jyväskylä, at the shore of Lake Jyväsjärvi and Tampere, at the shore of Lake Näsijärvi related to phases of freezing of those lakes. Generally differences in air temperature are not large, but in one mild year (winter 1924–25) the smaller Lake Jyväsjärvi (area 4.5 km^2) froze considerably earlier (25 November) than the deep lake Näsijärvi (20 December). In another year (winter 1929–30) they both froze about as late as each other (28 and 30 January), although on the average the end of the year was even warmer. For the period 1912–31 Lake Jyväsjärvi froze on average on 27 November, with Lake Näsijärvi later on 19 December due to the slightly warmer climate and greater depth and area. This stresses the importance of natural variation in climate and the differences in ice dates.

The model

The lake model in this paper is discussed mostly concerning the parts involved in determining the ice cover. Other sub-models are only briefly mentioned. The model is used in solving all the years in succession using continuous meteorological data as input. The model is the vertically resolving PROBE model, which solves second-order differential equations to obtain the vertical temperature profile in lake water. Turbulence is solved using horizontal velocities and a $k-\varepsilon$ model with equations for turbulent kinetic energy and its dissipation rate. All of the profiles are solved successively for each time step. Convection is also included in the model. Essential adjustments are made to the lake surface exchange and

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the modifications needed for the input. The long term meteorological input data and lake data used in calibrations are described in detail by Elo (2004) concerning the results of summer time calculations. In this study attention is given to wintertime and special questions involved are: the relation to temperature of air, processes of ice growth and decay and their description in the model. During open water period turbulence affects water: before freezing it has an effect on the cooling of the water. After ice cover is formed the surface is closed and the water is shielded.

The cumulative negative air temperature is used to determine ice thickness for growth and cumulative positive air temperature to calculate melting of ice. The surface heat flux during winter is approximated to see whether it favors ice growth or melt. This method has been found suitable for lakes, because there are processes compensating each other and when white ice and snow exist less black ice is formed (Adams 1981). Therefore for many purposes growth can be described as

$$\eta = K_g [\Sigma(-T_a)]^{1/2}, \tag{1}$$

where η is the thickness of the ice in metres, $K_g = 0.02 \, \text{m/}°\text{C}^{1/2}$ describes snow-covered ice and $\Sigma(-T_a)$ is the sum of the average air temperature over the days when the temperature is below freezing point (Elo *et al.* 1998). During the melting phase T_a is positive or zero, and in the model the daily decrease in ice thickness in metres is given as

$$\Delta\eta = K_m T_a, \tag{2}$$

where $K_m = 4.3 \times 10^{-3} \, \text{m°C}^{-1}$. These parameter values were based on earlier wintertime calculations (Huttula *et al.* 1992). The temperature sum is calculated and related to growth or melt, depending on the direction of approximated energy flow. The obtained ice thickness (and its cold content) is a new reference value for the temperature degree sum, giving successive periods of ice growth and melt. If air temperature remains close to zero the result can also be successive periods with ice and without it and numerous problems can follow. This period is anyhow difficult to model one dimensionally. Freezing and break-up of ice over the whole surface take some time, depending also on the smoothing of horizontal variations. When the air temperature changes are fast and large over 0°C these transitions occur rapidly and processes are easily described.

In the model heat balance is approximated during winter. The most important simplification is that evaporation is neglected and given a zero value during ice cover. Temperature of snow cover is also approximated and air temperature is used when temperature is below zero. Snow surface temperature is assumed to be zero during melting; this is found to be a good estimate (Cheng 2002). The surface balance estimate can also be used in deciding whether ice cover has been formed.

The degree-day factor K_m includes the combined effect by all the factors affecting the climate, the values depending on surrounding conditions. A study of its values over Finland was performed by Kuusisto (1980). He found that the effects of various factors are often difficult to resolve. Precipitation was effective, but the effect of radiation was not clear. Generally he could find the following features: the values are larger in the south than in the north, and in open rather than forested areas and the values grow larger as the spring gets longer. This information was used to change the values of K_m relative to the value used for Lake Pääjärvi, which was used in the calibration of radiation data. For Lakes Jääsjärvi and Kiimasjärvi $K_m = 4.8$ was a more suitable value, representing faster melting in small and sheltered lakes. Changing the value used during autumn usually gave practically no effects, but for Lake Pielavesi with $K_m = 2.5$ a relevant improvement was obtained and ice was not formed too late. This can again be related to relatively strong flows in that lake.

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In the model ice cover is formed when calculated surface water temperature cools enough. Usually the limit is 0°C, but for Lake Näsijärvi it had to be lowered to -2.5°C, otherwise the ice cover was formed too early. For Lake Näsijärvi an exceptionally small value was suitable: $K_m = 2.5$, which mostly corresponds to dense forest. When ice is formed it covers the water and changes the energy exchange with the atmosphere. Usually also flow conditions become calmer under ice, because wind stress is prohibited and turbulence equations are not solved any more. If the ice thickness is smaller than 0.05 m ice break-up occurs and conditions are changed accordingly. That happens also if wind speed is larger than a maximum value of 6 m/s and ice thickness is less than a given limit value (0.1 m). This can be caused by water surface motion induced by wind: thin ice can be cracked by strong winds. For one of the lakes the model could be adjusted better by changing this maximum wind limit value: for Lake Jääsjärvi 7.5 m/s was used.

Ice and snow affect the amount of heat absorbed by water. Exponential attenuation describes this in water, ice and snow. In water absorbing heat is described as a source term for the differential equation of heat over the vertical. For ice cover separate layers can be defined for black ice and snow. Light can heat water through ice cover, but most of the light is absorbed in the ice and particularly in snow and white ice. Measurements from the Finnish Environment Institute (SYKE) could be used to estimate snow cover. Those measurements included measurements of the thickness of total ice cover, snow cover and slush ice together with water level in the whole observation area compared to ice surface. These were available for the lakes in the vicinity from eleven sites for several years. Those measurements have been made according to the methods described by Palosuo (1965) over several years. For lakes in the area typically the ice thickness was about 30 cm, when snow was melted. That depth of black ice allows relatively small amounts of light into the water. The snow cover was therefore not treated separately. Later in the spring penetrating light becomes relatively larger and the water is warmed more below the ice. Then direct melting from above is also considerable and the ice is melted rapidly.

Calibration and validation

The study was made as a sensitivity analysis and looking for systematic changes to make the results better. Changes were made to the parameters, which could be associated with physically meaningful factors and conditions. The success of the simulation of lakes is very much dependent on the available lake data, which can be used for calibration and adjusting the model. It was possible to collect enough information for a total of seven lakes. Four of them have been adjusted in a study concentrating on the summer season (Elo 2004): Lakes Jääsjärvi, Näsijärvi, Kallavesi and Pääjärvi. In addition to these, three more lakes with a lot of ice data were simulated: Lakes Kiimasjärvi, Koivujärvi and Pielavesi. The first two are small lakes and their winter time simulation was possible by applying information based on earlier studies. On the other hand, it was not possible to control the summer season as well due to lack of data. Lake Pielavesi is rather large and complicated due to its shape. Actually it is formed by two lakes (Pielavesi and Nilakka) with a canal between, but it was possible to use surface temperature soundings from the canal to adjust the model to study the results of winter ice cover. Later, only Lake Pielavesi is mentioned to abbreviate it and the ice observations are from that. The observed ice dates from Lake Nilakka are very close to those from Lake Pielavesi anyhow.

Primarily average values were looked at from the output, together with corresponding standard deviations. Also maximum and minimum values and strongly deviating years were studied. Modifications were made until the resulting difference between calculated and observed dates on average was less than one or two days. Due to strongly deviating years

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there are large values changing the mean value: better results could be assumed to be obtained taking into account conditions during those more exceptional years.

For ice formation the basic model gave on average about 10 days too early a date for Lakes Jääsjärvi and Pielavesi, and 9 days too late for Lake Näsijärvi. For the other lakes the differences were only one or two days, so the suitability was rather good already without modifications. For ice break-up the largest difference was for Lake Näsijärvi, about 10 days too early, while for the others it was right by less than four days.

The results

Statistics of ice data (Tables 2 and 3) are considered for the years 1916–1949 and 1950–1997. The results for these sub-periods are given separately because meteorological input data from them are not fully comparable. The data from basically one station were successfully used for a number of lakes in the surrounding area. Level corrections were needed to take account of basic differences according to the locations, but lake data were made for final adjusting. Calculation of summer season stratification is more dependent on local climate variations. The winter period is more easily solved, if surface water temperature can be used for calibration. Two lakes were calibrated using ice data. As long as the water is ice-free especially the depth of the lake concerned is most important, due to the heat stored in water. Also horizontal effects are of importance.

Later freezing and earlier break-up have been observed over periods of decades and centuries (Magnuson et al. 2000). Most of the ice date series in this study were included in that material. During the beginning of the 20th century the lakes in Finland froze relatively late (seen also in Figure 2), compared to other lakes and rivers seen in their study, and also noted by Kuusisto and Elo (2000). Break-up dates had about the same trends towards earlier dates as other compared lakes and rivers (Figure 3), and ice breaks up about one day earlier for the later dates. The sub-periods 1916–1949 and 1950–1997 are anyhow rather short and the results for individual lakes could vary. When trends were plotted on the ice date series for some lakes they were even opposite for the different periods. When sub-period averages were compared the difference is larger for freezing, while in the former period the lakes froze

Table 2 Freezing of the lakes studied. The dates are given as the number of days before the start of the year. N is the number of observations, corresponding values of the calculated values are used for the difference between observed and calculated dates. SD is the standard deviation

Lake	N (1917–1949)	Observed (SD)	Calculated (SD)	Obs.-calc. (SD)
Jääsjärvi	31	40 (15)	35 (21)	5 (14)
Kiimasjärvi	32	41 (14)	45 (15)	− 4 (11)
Koivujärvi	34	47 (14)	45 (14)	1 (9)
Pielavesi	20	45 (15)	39 (18)	10 (19)
Näsijärvi	34	11 (18)	13 (23)	− 2 (10)
Kallavesi	34	23 (17)	28 (18)	− 6 (9)
Pääjärvi	13	18 (24)	20 (23)	− 5 (11)
Lake	**N (1950–1996)**	**Observed (SD)**	**Calculated (SD)**	**Obs.-calc. (SD)**
Jääsjärvi	36	44 (12)	44 (14)	0 (11)
Kiimasjärvi	9	46 (11)	50 (9)	− 4 (5)
Koivujärvi	44	52 (12)	51 (11)	1 (8)
Pielavesi	44	44 (11)	45 (12)	− 1 (8)
Näsijärvi	46	15 (14)	17 (18)	− 2 (13)
Kallavesi	46	31 (12)	32 (14)	0 (10)
Pääjärvi	36	21 (12)	27 (14)	− 3 (11)

Table 3 Ice break-up for the lakes studied. The dates are given as the number of days after the start of the year. *N* is the number of observations, corresponding values of the calculated values are used for the difference between observed and calculated dates. SD is the standard deviation

Lake	*N* (1917–1949)	Observed (SD)	Calculated (SD)	Obs.-calc. (SD)
Jääsjärvi	31	126 (10)	129 (10)	− 2 (4)
Kiimasjärvi	33	129 (9)	131 (10)	− 2 (5)
Koivujärvi	33	133 (8)	136 (9)	− 3 (4)
Pielavesi	20	134 (7)	136 (10)	0 (3)
Näsijärvi	33	133 (9)	135 (11)	− 2 (5)
Kallavesi	33	127 (10)	130 (10)	− 3 (4)
Pääjärvi	14	124 (12)	124 (11)	− 1 (5)
Lake	***N* (1950–1997)**	**Observed (SD)**	**Calculated (SD)**	**Obs.-calc. (SD)**
Jääsjärvi	45	125 (8)	127 (7)	− 2 (8)
Kiimasjärvi	29	128 (6)	129 (7)	− 1 (4)
Koivujärvi	43	132 (5)	133 (7)	− 1(4)
Pielavesi	45	133 (6)	133 (7)	0 (4)
Näsijärvi	43	132 (7)	132 (8)	0 (5)
Kallavesi	46	127 (8)	128 (7)	− 1 (4)
Pääjärvi	24	123 (8)	122 (7)	1 (8)

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about four days earlier. Climate variations may be more important for freezing: in spring ice break up is strongly determined by air temperature, but for freezing the heat stored in water and its cooling rate also have an effect. This also varies for different kinds of lakes. There are also changes in variances of ice observations: at the beginning of the century variations were slightly larger than they were at the end. Variances are also larger for observed freezing dates than for ice break-up.

For the later period the correspondence between observed and calculated ice dates is better. The model could also describe well the earlier period, with slightly larger variations for calculated values. For the later period calculated variations were also closer to those observed. There were still some strongly deviating years. Anyhow, those are connected to deviating climatic conditions, when usually the temperature of the air was above zero for a sufficient time and higher than usually for that time of the year. The model would need development to be able to present such conditions: at least, the constants included in models would probably need to be changed to fit the conditions. That can be problematic to carry out.

The model is based on physical conditions and it can solve both parts of the century almost as well, in spite of data problems. This further supports the view that the model can be applied to a variety of lakes, and a lot of old classical lake data can also be used in connection with it. This can be of importance in the future in studies of natural changes occurring in lakes. Changes can be very fast and strong, and also older data can be valuable in studies of long-term effects, e.g. for comparisons. Variability found in biology is large and sometimes some studies, although short, can be among the few made about certain phenomena. It might be important to be able to unite these studies with others to gain the best results with limited resources for studies.

For freezing better results were obtained changing the limit for wind breaking the ice for Lake Jääsjärvi. This can be thought to be caused by the broken shape of its surface area: it makes it harder for wind to break the ice. For Lake Näsijärvi the temperature limit for freezing was lowered; it has the largest surface area and freezing of the whole area can take rather a long time during which parts of the lake have already frozen, lowering the average

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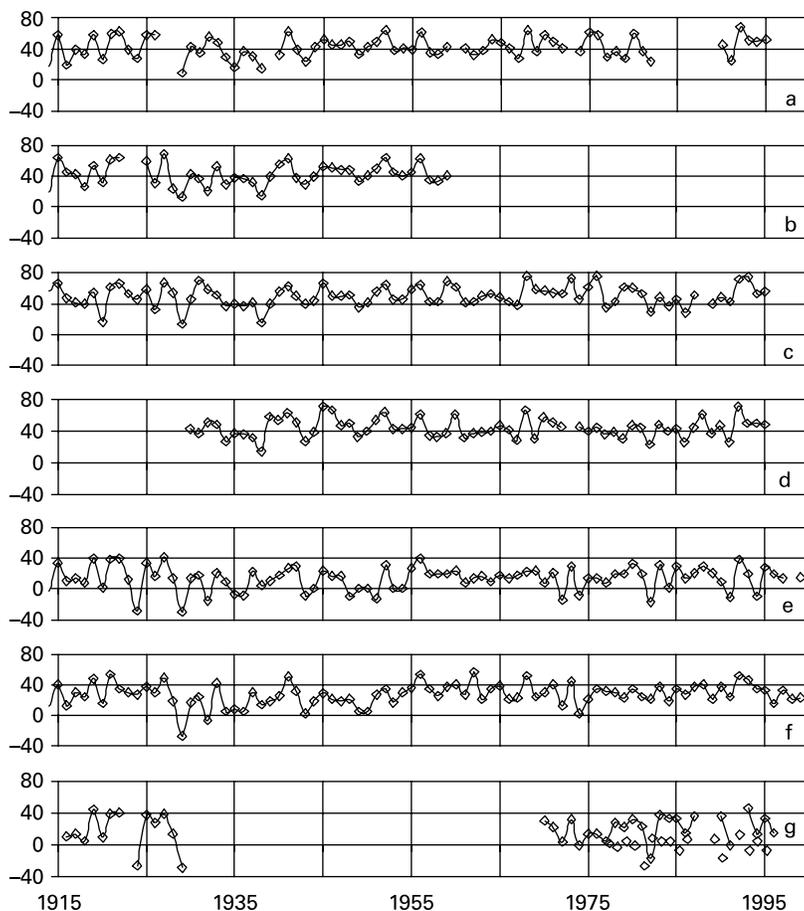
Figure 2 Formation of ice in the study lakes. The number on the y-axis is the number of days before first of January for the day the ice is formed in the year given on x-axis. Open squares are observed values, black squares are calculated with the PROBE-model. The lakes: a) Lake Jääsjärvi b) Lake Kiimasjärvi c) Lake Koivujärvi d) Lake Pielavesi e) Lake Näsijärvi f) Lake Kallavesi and g) Lake Pääjärvi

surface water temperature used as a limit. Strong flows cool water fast at Lake Pielavesi at the observation site used for calibration of the surface temperature. For its application it was suitable to reduce the coefficient for melting during autumn, then ice was not formed too late. For ice break-up better results were obtained when the degree factor was varied, corresponding better to the values corresponding to the local conditions. To the south melting is faster due to more intense global radiation and higher temperature of the air. Openness of the site is of great importance, while in sheltered conditions melting is not so fast. For Lake Näsijärvi there must be some other factors affecting it. There the observation site at the shore can be rather sheltered, although the whole area is one of the largest modeled and could well represent open areas.

Difficulties arise during exceptional years, typically during winters when the temperature of the air remains close to, or above, zero for too long. Late freezing or even melting periods in the middle of ice covered periods can then occur. During short ice covered periods also, for example, the importance of snow cover and direct heating by insolation under ice can have greater importance. These can sufficiently change the situation in spring and it is not enough to start from some assumed situation at a certain date in spring, as is done in some

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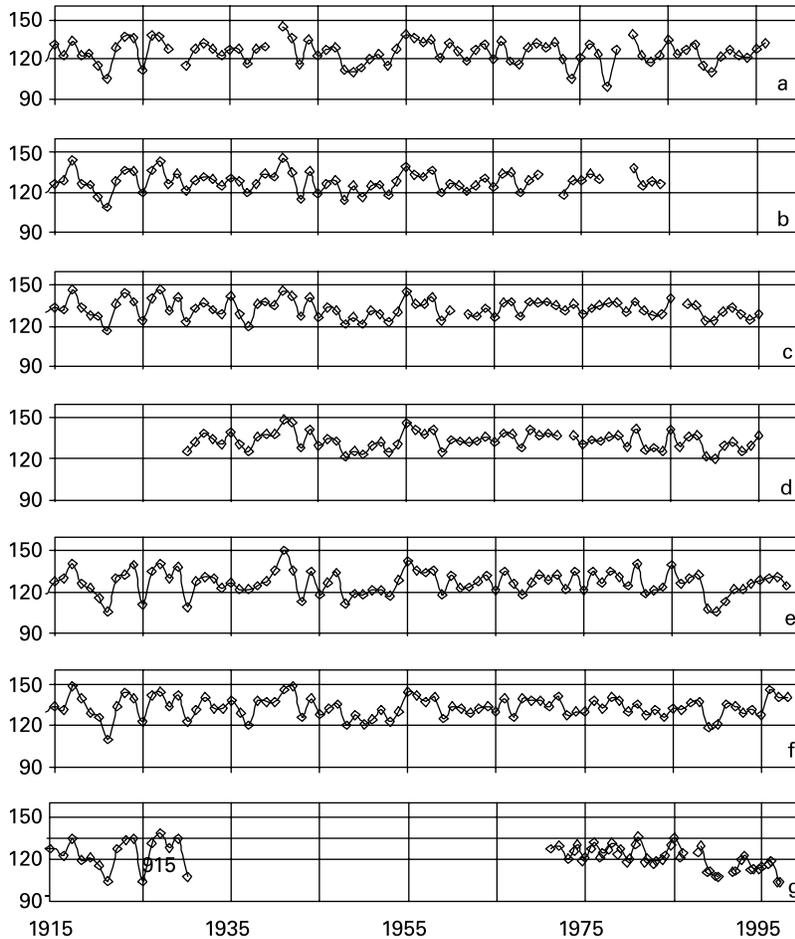
Figure 3 Ice break-up in the study lakes. The number on the y-axis is the number of days after first of January for the day the ice is broken up in the year given on x-axis. Open squares are observed values, black squares are calculated with the PROBE-model. The lakes: a) Lake Jääsjärvi b) Lake Kiimasjärvi c) Lake Koivujärvi d) Lake Pielavesi e) Lake Näsijärvi f) Lake Kallavesi and g) Lake Pääjärvi

studies. For some effects it can be important if certain conditions occur for many years in succession. These deviating climate conditions can also occur in successive winters. All these reasons support the idea that years should be calculated in succession, which was noted also by Peeters *et al.* (2002).

As well, numerical problems can disturb calculations, e.g. freezing can be calculated to occur too often, disturbing the solution of water temperature. Leppäranta (1993) has also noted that a model with more detailed descriptions would need finer time steps during freezing. This supports the need for more developed models for periods which are outside the range of typical conditions used: if climate warms so that the average air temperature during winter time is going to rise for relatively long periods and often, it is very likely that any model tuned for circumstances with clear separate long periods of ice cover is going to have difficulties with warmer winter conditions. Newer models should be developed accordingly. It is also important to remember that if similar conditions are sought from some other location (or time) it is possible that all the features of the climate are not similar enough, e.g. the importance and effects of snow can be different under slightly different climate

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conditions. For solving such questions physically based numerically solvable mathematical models with exact solutions give the possibility to estimate, compare and verify.

Discussion

At the beginning of the 20th century the lakes in the Finnish Lake District froze late, which indicates that the autumns were milder then. On average they froze four days earlier, the difference ranging from -1 to $+8$ days for individual lakes. Ice break-up has occurred more smoothly with a persistent trend towards earlier break-up: the average shift of about one day per decade is seen also for the averages. There are changes also in variances towards the end of the century: for freezing a decrease of about five days and for ice break-up about two days. The ratio has remained and the variance for freezing is almost twice as much as that for break-up.

The clearest mark of the effects of morphology is that deep lakes freeze about one month later. This is due to the heat stored in the water and its slow cooling. Sheltering is important for small lakes, it favors early ice formation, but that effect is only of about one week. Also strong currents favors early freezing via enhanced cooling. The variances of observed freezing between different lakes are rather close to each other. For freezing the average differences between the earliest and latest break-up dates are only about ten days. Also the variances are small. It is hard to find clear signs of the effects of morphology from the observations of ice break-up.

These features can be repeated systematically with the PROBE model. The correspondence can be improved with simple changes in the parameters used, which can be associated with physically meaningful and natural explanations which can be associated with morphological features. The meteorological input data were from the middle part of the lake district and they were modified by considering data from surrounding stations and studies concerning them. The older meteorological data included human observations made estimating the position of a wind vane, but it suited the purpose rather well, with only slightly weaker correspondence with the observed ice dates. This is of importance, because there are not many sites where natural wind data are available (Stewart and Haugen 1990).

If winters become warmer the amount of light under thinner ice becomes more important. It can locally increase biological activity and absorbance. Biology can in principle be affected due to the changed light climate under ice although thermal conditions would not be changed much. Naturally the most important change would be the absence of ice cover in areas where it usually has been covering and protecting lakes. During warmer winters these periods occur more often, raising the importance of their description in the models. These features are worth development accordingly.

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