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The effects of climate change on the temperature conditions of lakes

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Climate change, as indicated by changes in air temperature, was simulated with the SILMU (the Finnish Research Programme on Climate Change) scenarios. The effects of air temperature change on the temperature regime of five lakes were studied with a temperature model using two approaches. The parameters describing the temperature regime were vertical temperature distribution, length of the stratification period, time of freezing and time of ice break-up. The surface areas of the lakes range from 0.25 km^2 to 161 km^2 and depths from 13 to 85 m. For one lake (Pääjärvi) the averages and the standard deviations of the temperature parameters in a changing climate were computed for the years 2036–2065. For the year 2050 (June–August) the surface temperature increases by 1.8 °C, and the low and high estimates are 0.5 °C and 2.6 °C. For the other lakes a spatial approach was used. Representative values for air temperature in the years 2020, 2050 and 2090 were used to obtain a spatial description of the temperature regime of small lakes all over Finland. All the results showed significant changes in the temperature regime, e.g. changes of 30–60 days were predicted in the length of stratification and ice-covered period.

Introduction

Within the framework of the Finnish Research Programme on Climate Change (SILMU), a lake model was used with the simulation schemes recommended by SILMU in order to obtain as much information as possible on the lake water temperature changes expected to occur due to climate change. We present here results from the simulations for five Finnish lakes (Fig. 1). This article concentrates on the temperature conditions of lakes, including the ice-covered period. The objective was to study the sensitivity of the ice cover and the thermal regime of lakes to imposed changes in meteorological variables representing climate change. The responses on a nationwide scale were included by studying various lakes around Finland, and also by making sensitivity tests with a lake equivalent which had the physical characteristics of Lappajärvi.

Fig. 1. Location of the lakes studied (squares) and the weather stations used (dots).

Research on climate change ranges from studies using large-scale global models to small-scale studies. The study of lakes, especially on the mesoscale level, forms an important part of a broader interest in complex hydrological and meteorological systems. Biology is also affected in important ways. Various physical lake processes can be associated with time scales, e.g. mixing due to storms and topographical waves (days), annual stratification cycles (weeks and months) and phenomena connected to the yearly cycle (e.g., Imboden and Wüest 1995). The surface temperature of water bodies is also relevant for assessing areal values of evapotranspiration from heterogeneous surfaces. Small lakes are subject to various sheltering effects. Lake modelling can also bring valuable information both for downscaling results of the GCMs (Global Circulation Models) and for the aggregation of their input data. Lakes can serve as indicators of climate change, and whether they are ice-covered or not is extremely important for the radiation balance of the earth's surface. The albedo of water is much lower than the albedo of ice, especially snow-covered ice. Thus, lake surface conditions can be important for climate feedback processes.

Various scenarios have been used in climate change studies. We used the SILMU scenarios (Carter *et al.* 1996) as described in detail below. Three of the scenarios are so-called SILMU policy-oriented scenarios, which try to capture the range of uncertainty in estimating the future climate over Finland. They account for two major uncertainties, namely future greenhouse gas emissions and climate sensitivity, and they also give seasonal changes. The two SILMU scientific scenarios provide more spatial and temporal details.

Some previous studies related to climate change

Hostetler (1995) discussed one-dimensional lake models and their applicability to modelling the effects of climate change. He also pointed out the data requirements necessary to achieve accurate modelling. He demonstrated how thermal and lake-level models can be used to reconstruct historical and paleolake levels. Crowe (1993) incorporated a water-balance-salinity model to evaluate the sensitivity of a lake dominated by groundwater to climate variability and long-term climate change. A long-term water and energy balance model was used recently by Vassiljev *et al.* (1995) in Estonia to study the period 1940–1990 using monthly weather data. They found the model suitable for investigating the impacts of climate change on a lake. Using remote sensing to assess the regional impact of climate change, Hall *et al.* (1994) found important regional differences e.g. in the structure of the ice. Assel and Robertson (1995) used long-term lake-ice records to study the region of the Great Lakes. The sensitivity of Wisconsin lake ice to climate variations was studied by Vavrus *et al.* (1996). According to their results a mean annual air temperature rise of 2.4 °C would cause the shortening of the ice-covered period by 24 days. The surface albedo and its relation to ice cover were considered for example by Oerlemans and Bintanja (1995).

The ice formation and break-up time and the length of the ice-covered period were used as climate indicators by e.g. Simojoki (1961), Ruosteenoja (1986), Kuusisto (1987) and Kajander (1993). Thendrup (1985), and Laasanen and Forsius (1988) discussed temperature models and measurements methods. Kuusisto (1981) studied the water temperatures of Finnish lakes for the period 1961–1975. Kuusisto also found that a warmer climate could result not only in shorter ice-covered periods but also in the possibility that the deep, large lakes in Finland would not freeze over every year (Kuusisto 1989). The results of all these studies desribe the Finnish conditions well. Haapala and Leppäranta (1997) simulated the expected Baltic ice conditions, showing that the fast ice period for the northern part of the Gulf of Bothnia will be 27 days shorter in 2050 than in 1961–1990, and the maximum ice thickness will decrease by 23 cm.

Croley II (1995) provided results on the effects of climate change on the Great Lakes of North America that usually only partly freeze over. A one-dimensional ice model was used to relate the extent of ice cover to meteorology, heat storage and surface fluxes. The simulations showed increased heat storage, which will cause reduced ice formation during winter. His results also indicated that the yearly cycle of these deep lakes might change in some years. For Lake Erie, the simulation showed that if atmospheric CO_2 doubled, the minimum temperature in the lake would not go below the point of maximum density in one year out of four. For shallow Lake St. Clair, which belongs to the region of the Great Lakes, this was not seen. The start of the summer stratification period can also change, thus showing also the importance of predicting changes in wind conditions.

The PROBE lake model

The PROBE lake temperature model, which was applied in this study, is one-dimensional along the vertical. Mixing in the water is calculated using a *k*-turbulence model developed by Svensson (1978). Applications of Svensson's model for ocean and lake are described in Omstedt *et al.* (1983) and Sahlberg (1983, 1988a). Burchard and Baumert (1995) performed analyses of the constants of the turbulence portion of the model. Detailed descriptions of the application of the model can also be found in Virta *et al.* (1992, 1994, 1996), Huttula *et al.* (1992) and Elo (1994). The model used in the SILMU studies was further modified to include features which can be used to predict lake water chemistry and ecology (Malve *et al.* 1991, Bilaletdin *et al.* 1993). That model version was used for studying the effects of climate changes on lake water chemistry and biology by Frisk *et al.* (1997).

In the SILMU studies model, in which a lake is described as a pile of boxes, the area-depth curve can be used to include the horizontal factors in the calculations. The effects of horizontal pressure gradients can be included by using a special seiche simulation. However, various other horizontal phenomena connected to bottom topography, circulation, advection and waves cannot be included in the calculations. Their importance to a particular lake has to be considered separately, also taking into account time scales. The variables are numerically solved with second-order differential equations representing the one-dimensional average at the corresponding depth. The solved equations are based on the Navier-Stokes equations, using the Boussinesq approximation. The model includes equations for horizontal velocities, heat content, turbulent kinetic energy k and its dissipation rate ε. The dynamical eddy viscosity μ_T is calculated with the second-order closure:

$$\mu_T = C_\mu \rho k^2/\varepsilon \tag{1}$$

where $C_\mu = 0.09$ is an empirical constant and ρ the density. When the deep lakes Pääjärvi, Lappajärvi and Sarmijärvi were simulated, the so-called deep mixing term $-\rho_{\mathrm{ref}}A_s/N$ was added. There r_{ref} is the reference density 999.975 kg m^{-3}, the constant $A_s = 2 \times 10^{-7}$ and $N = \sqrt{-(g\Delta\rho)/(\rho\Delta z)}$ is the Brunt-Väisälä frequency (Stigebrandt 1987).

The momentum flux into the water is calculated using wind velocity. The atmospheric longwave radiation is determined as a function of air temperature, relative humidity and cloudiness. Cloudiness was calculated from the record of short-wave radiation in the applications describing Pääjärvi. Sensible and latent heat are computed from aerodynamic formulas, which means that the wind speed is also required as an input. Some of the short-wave radiation is reflected from the surface, some is absorbed in the very top layer and the rest is absorbed in the deeper layers. Absorption is described with an exponential bulk formula, and the extinction coefficient is given as input.

The formation of ice is described with the degree-day method, and the melting with the temperature index method. The growth was calculated according to Huttula *et al.* (1992):

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

where η is the thickness of the ice in meters, $K_g = 0.02/°C^{1/2}$ describes snow-covered ice, and $S(-T_a)$ is the sum of the average temperatures of the days when temperature is below the freezing point. During the melting phase, the daily decrease in ice thickness in meters is described by

$$\Delta\eta = K_m T_a \tag{3}$$

where $K_m = 4.3 \times m°C^{-1}$, and T_a is positive or zero. The values of the constants depend on the local conditions, which were described by Kuusisto (1984) and Vehviläinen (1992) for the vicinity of Pääjärvi in particular and for Finland in general. The constants used were found to describe well the ice formation, growth and break-up for Lappajärvi (Huttula *et al.* 1992).

This method describes the energy balance of snowpack using primarily air temperature. The main features of the winter development of the ice cover can be solved with this simple approach. The actual formation and melting of ice are complicated processes involving heat exchange and metamorphosis in various layers of the ice and its surroundings, and the formulation assumes that after the formation of ice there is a continuous ice-covered period until the ice breaks down (Lepparanta 1983). The values of the parameters may change during the winter due to changes in meteorological conditions, mainly in the air temperature, the short-wave radiation level and the albedo. We used constant values for the parameters for all the simulations because they can be assumed to provide a reasonably good estimate, especially when the changes are not well-known.

The snow cover for the reference period was studied by Solantie *et al.* (1996). Near Pääjärvi the permanent snow cover was formed on average about one week later and disappeared about two weeks earlier than the ice cover predicted by the model. The spatial simulations included separate descriptions of the attenuation of short-wave radiation in the ice and in the snow on it (Huttula *et al.* 1992), but in the transient simulations we did not separate snow and ice. The heat flux caused by the penetrating light under the ice with thin or no snow cover was found to be important in the small heat fluxes of rather small ice-covered Swedish lakes (Bengtsson and Svensson 1996).

The simulations of this study show that the continuous ice-covered period may break down into shorter periods and periods with no ice cover. This was also seen in the results obtained by Huttula *et al.* (1992). In the present study, the ice-covered period was defined as the last continuous period before summer.

The decrease in the ice thickness is proportional to the air temperature. The limits used in the model are set in such a way that the wind can also break the ice cover when its thickness is less than 10 cm and the wind velocity is over 6 ms^{-1} (Sahlberg 1988a, Huttula *et al.* 1992).

The lakes studied

Five lakes of different dimensions were studied (Table 1). Pääjärvi, which is the deepest of these

Table 1. Physical characteristics of the lake basins.

	Location	Area (km^2)	Mean depth (m)	Max. depth (m)	Retention time (d)
Pääjärvi	60°04´N, 25°08´E	13.1	15.2	85.0	1 200
Längelmävesi	61°25´N, 24°09´E	11.2	8.3	41.0	60
Kalliojärvi	61°55´N, 24°30´E	0.25	4.4	13.0	470
Lappajärvi	63°15´N, 23°38´E	161	7.4	38.0	910
Sarmijärvi	68°47´N, 28°12´E	4.6	4.5	27.0	120

lakes, is considered to be quite free of pollution. The sub-basin of lake Längelmävesi, limited by the straits of Pelisalmi and Kaivanto, is mainly influenced by agriculture and also by wastewater loading. Kalliojärvi is a small and shallow lake sheltered by hills on the eastern shore and affected by forestry measures. Lappajärvi is a relatively large, detached lake in western Finland, receiving runoff water mainly from agricultural land and forested basins. Sarmijärvi is a small lake in northern Finland which is used as the raw water source for a state-owned fish hatchery.

Applied scenarios

Carter *et al*. (1996) described the SILMU scenarios 1, 2, 3, 1a and 1c. The mean annual temperature change from the SILMU baseline period 1961–1990 to the year 2050 is 2.4 °C according to SILMU scenario 1. The corresponding low estimate is 0.6 °C (according to scenario 2) and the high estimate is 3.6 °C (according to scenario 3). Two SILMU scientific scenarios (1a and 1c) were also used in the simulations to show the types of differences that can be expected due to uncertainties concerning the pattern and magnitude of regional climate change. These two scenarios include the same annual temperature change as scenario 1. The scenarios give only the mean changes in the meteorological input variables but no changes in their variability. Therefore the variability of the observed climate data from the baseline period was maintained.

The climate change in the case of Pääjärvi was modelled transiently using all the original baseline data to obtain statistics over a long time period. Possible non-linear, rare effects due to system response to various input combinations are also more likely to be seen when the simulation is carried out many years in succession. The air temperature was changed gradually month by month according to the scenarios. Larger changes in the air temperature may make it necessary to modify the model-input routines using it. As the temperature changes were relatively small, this effect was ignored in this study. All other meteorological input variables were left unchanged with their original variations, which is reflected in the distribution of the effects. This approach is expected to give the main features of the effects.

Wind has a very strong effect on mixing and heat transport in the water body, but the scenarios do not provide estimates of expected wind condition changes. The radiation climate was not assumed to change. It is affected by cloudiness, changes in which are correlated to precipitation changes. Estimates on the latter still vary considerably, even in sign. The largest changes in cloudiness and radiation can be expected to occur in winter when, however, global radiation is small. These factors also affect the formation of ice, the snow cover over the ice and finally the ice break-up.

In addition to the transient simulations, for Pääjärvi another approach was used. Fixed monthly temperature changes in the year 2050 according to scenario 1 were added for each of the years of the baseline, while other inputs were maintained as constant. This is called scenario 1m in this study. Statistics were gathered as in the other simulations. These simulations should be comparable to the method that was used for the other lakes. Only one year was simulated. The data for this year were formed using statistics from the baseline to represent an average year. This was done with the weather generator developed for the SILMU studies (Carter *et al*. 1996), with which one can generate changes in temperature and cloudiness, which are assumed to follow changes in precipitation. Other changes in input are also estimated. Changes of the inflows were based on the study by Vehviläinen and Lohvansuu (1991).

Transient simulations of Pääjärvi

Baseline for the simulation

Pääjärvi is a small, rather deep lake which is usually stratified during summer. Two subperiods within the standard period, namely July–October 1969 (s69) and 1970 (s70), were studied earlier (Elo 1994). That study provided sensitivity estimates of the model and comparisons of the calculated and measured values. The present study used a slightly different type of data transfer presented by Virta *et al*. (1996). The calculated latent heat and radiation balance were on average 5% less and 3% higher, respectively, than the values determined from measurements during s69 and s70. The calculated surface temperature was on average 0.6 °C higher than that measured during s69 and s70.

These calculations, for both the baseline and the changed climate, were carried out by simulating all of the years in succession. There were also some irregular temperature measurements from different depths throughout the period 1961–1990. A comparison showed that the main features of the calculated and measured profiles were approximately the same. Determining the depth of the thermocline is always complicated with only a few point measurements. Eight observed ice formation and break-up dates were also available. The ice formation date was defined as the time at which the entire lake was observed to be ice-covered, and the ice break-up time as the point at which the entire lake was observed to be free of ice. According to these observations, the lake was frozen on 6 December (SD 19 days) and the ice broke up on 3 May (SD 8 days). On average, the simulated ice formation date was 5 (SD 12) days earlier and the break-up date was 3 (SD 6) days later than that actually observed.

Results with the transient simulations

The numbers in Tables 2 to 5 indicate the change in the sample means and the sample standard deviations of the distributions describing the situation in the changed climate in the year 2050. It was not possible to determine other parameters of the distributions due to the scarcity of data.

Table 2. Pääjärvi: changes in the length of the ice-covered period, in days, in the year 2050 due to temperature changes according to the SILMU scenarios compared to the baseline period 1961–1990. Also standard deviations and percentage of years with long non-continuous ice cover are given.

Scenario	A	B	C	D	E	F	G
1	21	32	30	24	12	56	38
2	0	4	9	4	2	8	11
3	55	35	24	34	17	68	28
1a	3	16	20	17	8	33	24
1c	38	12	18	16	13	29	25
1m	48	31	24	27	17	58	30

A = Percentage of years with long non-continuous ice cover.
B = Mean delay of ice formation date.
C = Standard deviation of ice formation date delay.
D = Mean precedence of ice break-up date.
E = Standard deviation of precedence of ice break-up date.
F = Mean shortening of ice-covered period.
G = Standard deviation of shortening of ice-covered period.

Ice-covered period

The results on ice conditions are given using the ice formation and break-up times and consequent duration of the ice-covered period (Table 2). For the standard period, the model gave these times generally well. Only one year had a rather long interval between the first simulated ice formation and the actual start of the long simulated ice-covered period. Six different years had a shorter interval of a few days between these.

With respect to the results of the simulations of future climate, the ice formation dates were more difficult to interpret straightforwardly. In some years, the simulated ice forms and melts many times in a period of one or two months. The percentage of these years in each simulation is also presented in Table 2.

In each simulated year with warmer air, the ice forms later and breaks up earlier than in the standard period. Only small changes occur according to scenario 2 with a low temperature increase. With a more significant rise in temperature (scenario 1), the effects are considerable and there are more years with periods of non-continuous ice cover. For some warm years it is not even possible to clearly discern a long ice-covered period. The results with scenario 1a include almost none of these periods, while scenario 1c gives almost twice the number obtained with scenario 1, whose temperature rise corresponds to both scientific scenarios. When the same fixed temperature change is used for each simulation year instead of the transient temperature rise, we obtain even more years with such periods, almost half of the total. All this suggests that it would be worthwhile to develop a better ice model to describe changed temperature conditions, taking into account other variables, such as radiation climate, snow cover, albedo and wind velocity.

Stratification and temperature during summer

During the summer, the epilimnion is formed due to a stable and relatively significant temperature difference between the surface layers and the deeper water, which warms more slowly. The surface temperature follows air temperature. If there are no clouds, the sun warms the water directly. With increased cloudiness, this direct warming is decreased due to shading, and the relative importance of long-wave radiation from the sky also increases. Wind causes mixing in the water and induces the important transfer of heat downwards. When the only change in the climate is a rise in air temperature, one would expect to see a rise in the temperature of the surface layers and a lengthening of the stratification period.

According to the simulations, the rise in surface water temperature (June to August) will be 1.8 °C (with scenario 1), with low and high estimates of 0.5 °C (with scenario 2) and 2.6 °C (with scenario 3) (Fig. 2a). Deeper than this, the change is projected to be small. The thermocline depth is not changed significantly. When the air temperature is higher, the stratification period starts earlier and ends a little later than during the baseline period (Table 3). The different scenarios do not seem to generate any specific features. The differences between the calculations using the transient and the fixed temperature rise are also practically negligible. A noticeable feature was that for the simulated temperatures at different depths the standard deviations are greater than the corresponding means and that the variations increase as temperature rises.

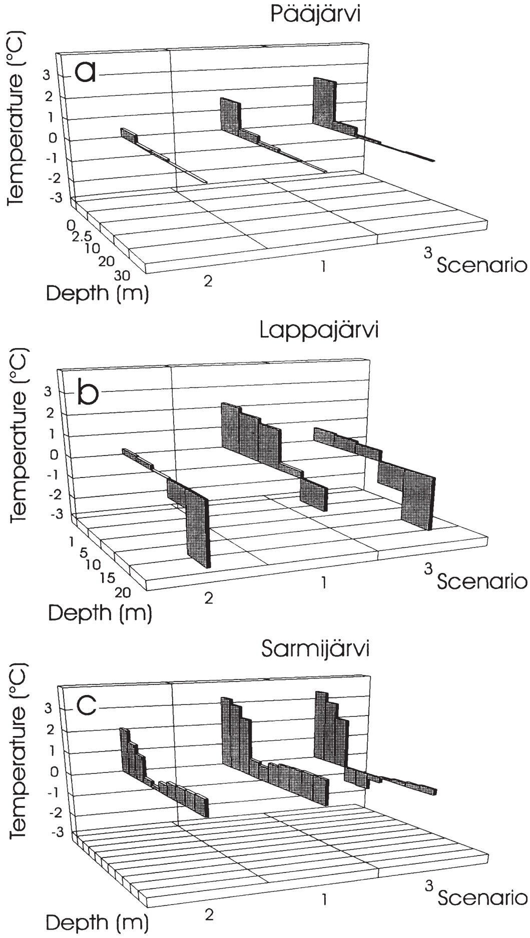

Fig. 2. Predicted temperature rise in July 2050 in (a) Pääjärvi, (b) Lappajärvi and (c) Sarmijärvi (depths 2.6, 4.9, 5.6, 7.9, 9.4, 11.6, 13.9, 15.4, 17.6 and 19.7 m). The scenarios are based on Carter *et al.* (1996).

Spatial simulations

The spatial effects are discussed here for the four case study lakes. The sensitivity test made with the Lappajärvi Equivalent (LE) also provided valuable information on the effect of latitude on the thermal regime of lakes during climate change. The results are based on SILMU scenario 1 for the years 2020, 2050 and 2090.

Huttula *et al.* (1992) simulated lake Längelmävesi, Kalliojärvi and Lappajärvi earlier by simply adding the predicted change in the input variables (air temperature, precipitation, discharge and snow cover) to the values of the variables. The predictions were made on the basis of fairly rough climate scenarios, with input data from different years. In the present study, these three lakes and also Sarmijärvi have been simulated by first describing the climatological average year, which

Table 3. Pääjärvi: predicted mean changes in the duration of summer stratified period and its standard deviation in days in the year 2050 due to temperature changes according to the SILMU scenarios compared to the baseline period 1961–1990.

Scenario	Mean duration change	SD of duration change
1	19	7
2	5	4
3	28	9
1a	17	6
1c	11	6
1m	19	5

represents the SILMU standard period, and then by modifying this period according to the SILMU scenarios. Some sensitivity estimates on the effects of changing wind and latitudes are included. The effects of changing boundary conditions have been studied for example by Henderson-Sellers (1988). In that study, the climatological input data used resulted in identical years after numerical stabilization.

The climate generator CLIGEN

The climate generator CLIGEN (Carter *et al.* 1996), was used to produce the meteorological data. This generator produces meteorological data so that certain statistical properties of the generated distributions correspond to the observed ones. Using CLIGEN, one can generate climate variables describing the present average climate, based on the SILMU period 1961–1990, as well as the future climate, which evolved according to the scenarios. The data for temperature, cloudiness and precipitation were obtained with the generator. Humidity was calculated as a regression of temperature and cloudiness from observations from the base years (1961–1990). The changes in snow cover on lake ice were calculated from the results of a regional watershed model (Vehviläinen and Lohvansuu 1991) as explained in Huttula *et al.* (1992).

Simulation of wind effects

Inclusion of wind input in the model is essential for the successful simulation of the lake water temperature. For the simulation of lakes with the spatial approach, the model was calibrated using certain years. The effective wind input was found for each lake so that the simulated water temperatures corresponded with the measured values in those lakes. The deviations of the calibration years from the baseline period were determined by using long-term wind data. The daily cycle and winds directions were maintained.

In this study, we were mainly interested in the effects of wind on the summer stratification. Realizing the uncertainty of the wind changes due to climate change, we limited our study to wind speeds higher than 7 m s^{-1} (fresh breeze). The effects of an increase in these winds were studied by simulating Lappajärvi and Sarmijärvi with an assumed increase of 15% and 30%.

The reduction of wind stress and solar radiation caused by the topographical features of the lake shorelines and the adjacent area was included in the spatial simulations according to Huttula *et al.* (1992) and as discussed by Sahlberg (1988b) and Jozsa *et al.* (1990). The wind data used were also observed at a nearby synoptic weather station, and thus they were not actual lake data. The main parameters for this calibration were the extinction coefficient and the wind velocity. In the case of lake Längelmävesi, winds were reduced by 90% from those observed at Tampere airport (Frisk *et al.* 1997) and in the case of Kalliojärvi by 40%–80% from winds at Kuorevesi, depending on the velocity and direction of the wind (Huttula *et al.* 1992). In the case of Lappajärvi, the wind velocity was slightly increased from the velocities observed at the Kauhava airport (Huttula *et al.* 1992). Because Sarmijärvi is small and surrounded by hills, the wind velocity values were reduced by 70%–80% from those observed at the Ivalo airport.

Results with the spatial simulations

Ice cover

The results of the ice cover simulations from all the lakes using spatial scenarios are presented in Fig. 3. In the year 2020 the change in the length of the ice-covered period will be fairly similar and not very large in these case study lakes. In 2090 the changes will be already clear and significant, although they depend on both the lake involved and its location. The model predicted that, generally the change in the melting time will be greater than the change in the ice formation time.

Water temperature and stratification

In the present climate, the water temperature of the surface layers during winter and spring is usually below the temperature of maximum density, and stratification takes place. Small amounts of heat can change the situation drastically. In the future, such a change can be caused even by an air temperature rise of only a few degrees. Changes in the wind-induced mixing can also have a considerable effect on the surface water temperature, also during the shortened ice-covered period. The decrease in snow cover on ice will increase penetration of short-wave radiation through the ice and will also heat up the water near the surface. Later during the summer, the stratification is more stable and the effects of climate change are not as drastic. These effects depend also on how easily the lake is exposed to winds. The following discussion is based on the results from the second summer, when the simulation results are not affected by the inital condions. The results are presented in Table 4.

The maximum increase will happen in May, when the lakes are weakly stratified in the present climate. Later in the summer, the change will not be as great, but the temperature will increase again in the autumn. The stratification period will increase considerably in all lakes. The water temperature in the hypolimnion will increase slightly. This increase was greatest (4 °C in August) in Lappajärvi, which is an open lake and exposed to the winds. The response of the lake surface temperature and stratification in summer to climatic change will be similarly fairly weak in 2020 as was the case of ice cover period. Also in 2050 the changes will not be so great, except in the case of Lappajärvi. In 2090 both the increase of water surface temperature and stratification period will show a very strong response to climatic change in a small and sheltered Kalliojärvi. There will be no spring turnover in the baseline period. According to the simulations, however, the lake will mix also in the spring in the years 2050 and 2090.

The effect of wind

If the lake is fairly big and open like Lappajärvi, neither the 15% increase nor the 30% increase in wind velocity will have any effect on the length of the ice-covered period in any of the three SILMU years. The increase in winds will mix the surface layers, and the heat will easily be transferred downwards. The increase in surface temperatures will not be as great as in the case of no increase in wind velocity. However, in the hypolimnion this vertical mixing will lead to a very significant increase in temperature.

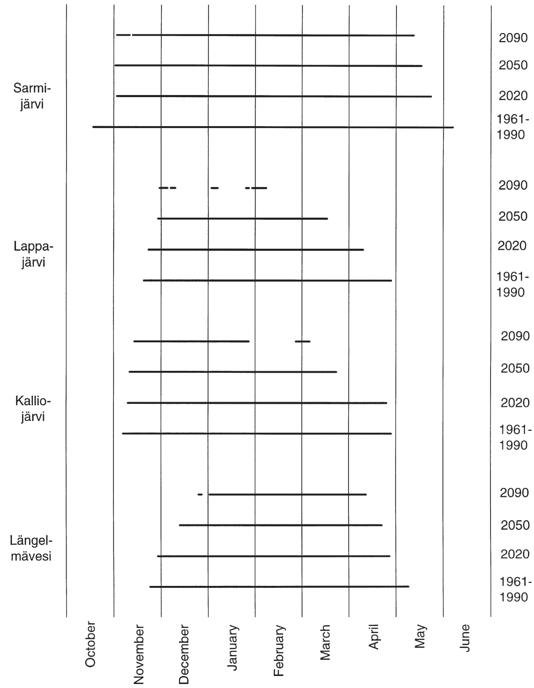

Fig. 3. Length of the ice-covered period in lakes Längelmävesi, Kalliojärvi, Lappajärvi and Sarmijärvi.

In the case of this small lake in Lapland the 30% increase in wind velocity will shorten the ice-covered period by about one week in the years 2050 and 2090. The 15% increase will not have any effect on the length of the ice-covered period.

Table 4. The maximum rise of temperature (°C) during summer and the increase of length of the stratification period in days compared to the present climate.

	Year		
	2020	2050	2090
Längelmävesi			
Temperature	2	3	5
Stratification period	16	31	48
Kalliojärvi			
Temperature	–	3	4
Stratification period	4	33	66
Lappajärvi			
Temperature	2	4	6
Stratification period	28	63	75
Sarmijärvi			
Temperature	2	3	4
Startification period	6	23	30

The effect of the wind increase is seen as a slight deepening of the thermocline and a slightly earlier occurrence of the autumn overturn.

The effect of latitude on an example lake

The Lappajärvi Equivalent (LE) is a hypothetical lake with the physical properties of the real Lappajärvi. Lappajärvi was chosen for this purpose because its thermal conditions are the most labile of all the study lakes. It was expected to reflect most sensitively the effects of changing latitude.

The following northern latitudes were selected (with the name of the nearest city with a weather station given in parenthesis): 61° (Lahti), 63° (Vaasa), 64° (Kajaani) and 69° (Ivalo). The air temperature and cloudiness values in a changed climate were generated with CLIGEN, using the spatial approach and scenario 1 as described earlier. The air humidity was calculated from the air temperature and cloudiness for each location.

Simulations showed that in the year 2050, the spring turnover (4 °C) will occur about one month later at Ivalo latitude than at Lahti latitude. At all latitudes, a thermocline will develop if winds do not change from the present. At Vaasa the thermocline will develop already in May. It will be destroyed again in a short time, however, and weak stratification will continue until the middle of August. At Kajaani latitude, the formation of stratification will begin at roughly the same time as the second stratification period at Vaasa latitude. At Ivalo latitude, the LE will stratify only for a short time in late July. The maximum epilimnetic temperature will occur at Kajaani and Vaasa latitudes in early July and near the beginning of August. At the Ivalo latitude, the maximum epilimnetic temperature will occur in late July. The hypolimnetic temperature in the middle of the summer (1 July) will exceed 12 °C at Vaasa latitude, 10 °C at the Kajaani latitude and 8 °C at Ivalo latitude. The autumn turnover will occur in September at 61 latitude and in late August at the latitudes of Vaasa and Kajaani. At Ivalo the turnover will occur as early as at the beginning of August.

Fig. 4 shows in detail the LE summer time (June to August) noon surface temperature changes at different latitudes from the baseline situation to the year 2050. The stratification period was determined with a temperature difference of 3 °C between the epilimnion and the hypolimnion. The depth of the thermocline was determined by finding the maximum temperature gradient at noon (July).

The changes are greatest in early summer like was found also with real study lakes. At Ivalo latitude, the maximum increase in temperature will occur about 1.5 months later than at the Lahti latitude. This maximum increase will occur at the depth of the new thermocline at the Ivalo and Vaasa latitudes, but at the Kajaani and Lahti latitudes the entire water column will have the same increase in temperature.

The change in the duration of the ice-covered period will decrease from the south of Finland towards the north up to the Kajaani latitude (Fig. 5). However, at the Ivalo latitude the change is projected to be even greater than in southern Finland. The length of the summer-time stratification period will increase more in southern Finland than in northern Finland. The mean surface temperature in June–August will be approximately 2 °C higher than today all over Finland. The mean depth of the thermocline in July will increase at the other three latitudes except at the Kajaani latitude, where it decreases.

These effects were not linear with latitude. This could be expected, as the climate zones in Finland vary spatially. The local atmospheric heat fluxes were calculated on the basis of air temperature, precipitation and cloudiness from CLIGEN. The variation of wind in the simulations was based on the observed wind data at the selected synoptic stations. It is obvious that the data from the synoptic station in Vaasa (at the 63° latitude near the coast of the Gulf of Bothnia) are affected by the sea. The station in Lahti (at the 61° latitude) is further from the coast of the Gulf of Finland, and the station in Kajaani (at the 64° latitude) is located even further from the sea. The Barents Sea in the north affects the meteorological conditions at the station in Ivalo (at the 69° latitude).

Discussion

The increase in epilimnetic water temperatures is quite evident in all of the simulated lakes. A rather similar rise was seen in all five lakes, except the one with largest surface area (over 100 km^2). This

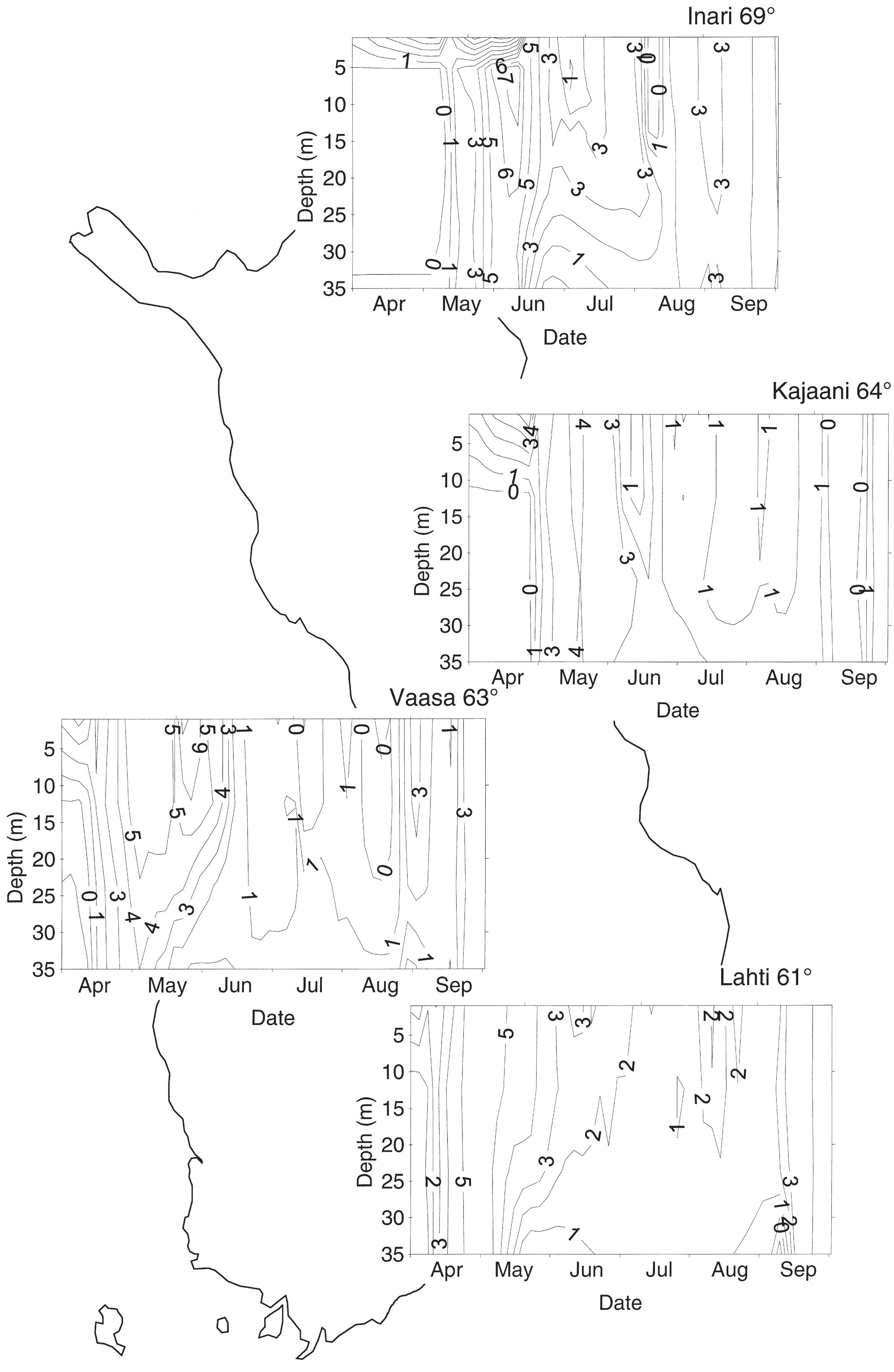

Fig. 4. Lake temperature change between baseline period and 2050 during April-August at different latitudes.

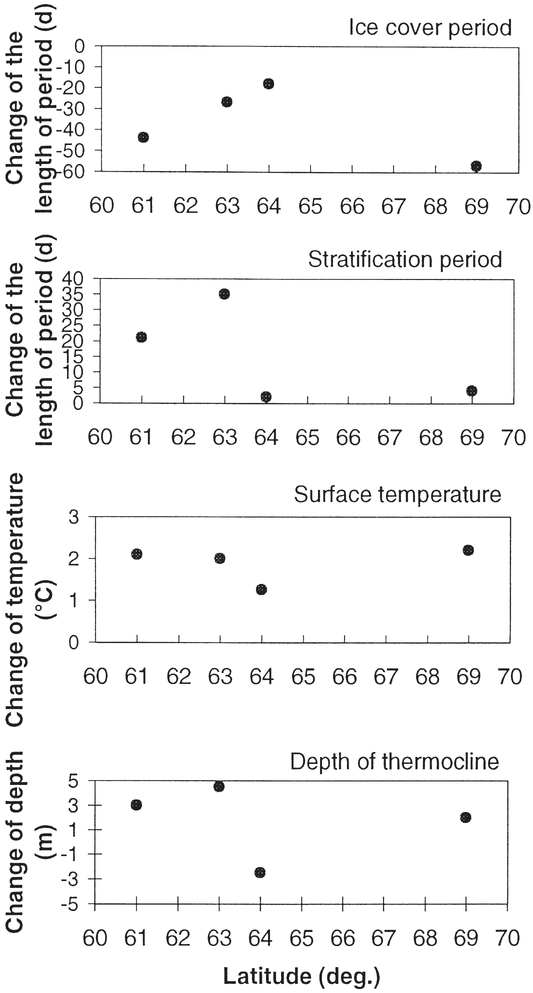

Fig. 5. Changes in the duration of the ice-covered and stratification periods, in the depth of the thermocline and in the temperature of the surface water at different latitudes between baseline period and 2050.

lake is most sensitive to winds, the effects and changes of which should be analyzed further. The increase will be a few degrees in May and also in June. In July and August, the increase will be more moderate. The increase in surface water temperatures will also increase biological production. As a result, more eutrophic lakes as well as algae bloom and other mass phenomena can be expected, with all their harmful consequences. This, of course, will also decrease the recreational value of these lakes. In this respect, all actions aiming to prevent eutrophication processes will now be even more valuable in the light of climate change. As to oligotrophic lakes, warmer surface waters may increase their recreational value for swimming, water skiing and other such activities.

According to these results the length of the stratification period will increase, especially in the deep lakes in southern Finland. The stratification period will be about 20–30 days longer and in larger lakes even twice that. This will have a close connection to the oxygen conditions in the lakes and also to biological activity. These lakes will experience more anoxic periods in the summer than at present. Life in the hypolimnion will become more difficult for various species, as the phosphorus release from the sediments will be increased. This will increase the phosphorus concentration first in the hypolimnion and later, as vertical mixing takes place, in the entire lake. This may lead to stronger and even new late summer alga bloom. The effect of climate change on nutrient and phytoplankton concentrations has been studied in detail by Frisk *et al.* (1997). Changes in the fish speciation in Finland have been studied by Lappalainen and Lehtonen (1997).

The future hypolimnetic water temperature in summer may be higher or lower than present, depending on sheltering and latitude. The increase in hypolimnetic temperature can be expected to be smaller in the deep lakes in northern Finland. The temperature in the hypolimnion has a very important effect on the speed of chemical and biological processes.

With the present ice model, it was not possible to obtain ice thickness distribution over the entire lake. The non-continuous ice-covered periods that were simulated can also indicate periods of partial ice cover. In such conditions the interactions between atmosphere and water are also very important. Further simulations of climate change would require also more knowledge of the radiation climate and albedo. Accurate calculations during the winter period are needed in order to make accurate predictions for the spring, which was seen in a recent field study of winter temperature conditions published by Malm *et al.* (1997).

Nevertheless, it can still be concluded that the thickness of ice in lakes will decrease and the ice-covered period will be considerably shorter than today. The shortening of the ice-covered period will have a positive effect on the wintertime oxygen conditions of lakes as the lake water will be aerated earlier than in the present climate. The expected decrease and condensing of the snow cover will lead to increased light penetration under the ice. This phenomenon, together with the earlier melting, is likely to provide suitable conditions for increased biological activity and for the growth of certain algae species in the early spring in eutrophic lakes. The ice cover can be expected to be weaker. This will affect wintertime activities such as fishing and roads on ice.

There are still other important questions that should be considered, such as humidity and water quality. An important deficiency in the temperature model is that it describes only a one-dimensional temperature distribution. This may be of special importance also in the description of temperatures in the littoral zone. The validity of the model used here for describing the heating of the hypolimnetic water is somewhat doubtful. The effect of this heating may be important when considering the cooling of water in the autumn.

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References

Assel A. R. & Robertson D. M. 1995. Changes in winter air temperatures near Lake Michigan, 1851–1993, as determined from regional lake-ice records. *Limnol. Oceanogr.* 40: 165–176.

Bengtsson L. & Svensson T. 1996. Thermal regime of ice covered Swedish lakes. *Nordic Hydrology* 27: 39–56.

Bilaletdin Ä., Frisk T. & Huttula T. 1993. Roineen vedenottoalueen veden laadun riippuvuus lähivaluma-alueen kuormituksesta ja Längelmäveden veden laadusta. *Vesi- ja ympäristöhallituksen monistesarja*, no. 512. 56 pp.

Burchard H. & Baumert H. 1995. On the performance of a mixed-layer model based on the *k-e* turbulence closure. *Journal of Geophysical Research* 100 (c5): 8523–8540.

Carter T., Posch M. & Tuomenvirta H. 1996. The SILMU Scenarios: Specifying Finlands future climate for use in impact assessment. *Geophysica* 32: 235–260.

Croley II T. E. 1995. Lauretian Great Lakes dynamics, climate, and response to change. In: Oliver Howard R. & Oliver Sylvia A. (eds.), *The role of water and the hydrological cycle in global change*. NATO ASI Series, Series I: Global Environmental Change, Vol. 31. Springer, Berlin, pp. 253–296.

Crowe A. S. 1993. The application of a coupled water-balance-salinity model to evaluate the sensitivity of a lake dominated by groundwater to climate variability. *Journal of Hydrology* 141: 33–73.

Elo A.-R. 1994. A sensitivity analysis of a temperature model of a lake examining components of the heat balance. *Geophysica* 30: 79–92.

Haapala J. & Lepparanta M. 1997. The Baltic sea ice season in changing climate. *Boreal Env. Res.* 2: 93–108.

Hall D. K., Fagre D. B., Klasner F., Linebaugh G. & Liston G. E. 1994. Analysis of ERS 1 synthetic aperture radar data of frozen lakes in northern Montana and implications for climate studies. *Journal of Geophysical Research* 99 (c11): 22473–22482.

Henderson-Sellers B. 1988. Sensitivity of thermal stratification models to changing boundary conditions. *Appl. Mathematical Modelling* 12: 31–43.

Hostetler S. W. 1995. Hydrological and thermal response of lakes to climate: description and modeling. In: Lerman A., Imboden D. Gat. J. (eds.), P*hysics and Chemistry of Lakes*. Springer-Verlag Berlin, pp. 63–82.

Huttula T., Peltonen A., Bilaletdin Ä. & Saura M. 1992. The effects of climatic change on lake ice and water temperature. *Aqua Fennica* 22: 129–142.

Imboden D. M. & Wüest A. 1995. Mixing mechanism in lakes. In: Lerman A., Imboden D. Gat J. (eds.), *Physics and Chemistry of Lakes*, Springer-Verlag, Berlin, pp. 83–138.

Jozsa J., Sarkkula J. & Tamsalu R. 1990. Calibration of modelled shallow lake flow using wind field modification. In: Gambolati G., Rinaldo A., Brebbia C. A., Gray W. G. & Pinder G. F. (eds.), *Comp. Methods in Surface Hydrology. Proc. of Eight. Int. Conf. on Computational Methods in Water Res.*, Venice, Italy, June 11–15 1990, pp. 165–171.

Kajander J. 1993. Methodological aspects on river cryophenology exemplified by a tricentennial break-up time series from Tornio. *Geophysica* 29: 73–95.

Kuusisto E. 1981. Suomen vesistöjen lämpötilat kaudella 1961–1975 [Water temperatures of lakes and rivers in Finland in the period 1961–1975]. *Publications of the Water Reseach Institute* 44. Vesihallitus — National Board of Waters, Finland, Helsinki, 40 pp. [in Finnish with English summary].

Kuusisto E. 1984. Snow accumulation and snowmelt in Finland. *Publications of the Water Reseach Institute* 55. Vesihallitus — National Board of Waters, Finland, Helsinki, 149 pp.

Kuusisto E. 1987. An analysis of the longest ice observation series made on Finnish lakes. *Aqua Fennica* 17: 123–132.

Kuusisto E. 1989. Snow and ice — non-renewable natural resources in the future? Conference on climate and water, Vol. I. *Publications of the Academy of Finland* 9/89. Government Printing Centre Helsinki, pp. 300–318.

Laasanen O. & Forsius J. (eds.) 1988. *Nordic Expert Meeting on River Ice*. Nordic Hydrological Programme, NHP Report No 21, Yliopistopaino, Helsinki, 243 pp.

Lappalainen J. & Lehtonen H. 1997. Temperature habitats for freshwater fishes in a warming climate. *Boreal Env. Res.* 2: 69–84.

Leppäranta M. 1983. A growth model for black ice, snow ice and snow thickness in subarctic Basins. *Nordic Hydrology*: 59–70.

Malm J., Terzhevik A., Bengtsson L., Boyarinov P., Glinsky A., Palshin N. & Petrov M. 1997. Temperature and salt content regimes in three shallow ice-covered lakes. *Nordic Hydrology* 28: 99–152.

Malve O., Huttula T. & Lehtinen K. 1991. Modelling of eutrophication and oxygen depletion in Lake Lappajärvi. In: Wrobel L. C. & Brebbia C. A. (eds.), *First Int. Conf. on Water Pollution: Modelling, measuring and prediction*. Southampton Sept. 1991, pp. 111–124.

Oerlemans J. & Bintanja R. 1995. Snow and ice cover and climate sensitivity. In: Oliver Howard R. Oliver Sylvia A. (eds.), *The role of water and the hydrological cycle in global change*. NATO ASI Series, Series I: Global Environmental Change, vol 31. Springer Berlin, 189–198 pp.

Omstedt A., Sahlberg J., & Svensson U., 1983. Measured and numerically-simulated autumn cooling in the Bay of Bothnia. *Tellus*, 35 A: 231–240.

Ruosteenoja K. 1986. The date of break-up of lake ice as a climatic index. *Geophysica*, 22: 89–99.

Sahlberg J., 1983. A hydrodynamical model for calculating the vertical temperature profile in lakes during cooling, *Nordic Hydrology*, 239–254.

Sahlberg J. 1988a. Modelling the thermal regime of a lake during the winter season. *Cold Regions Technology*, 15: 151–159.

Sahlberg J. 1988b. *Beräkning av winteruppvärmning och termoklinutveckling i Tulebosjön*. Rapport R79. Byggforskningsrådet. Stockholm, 20 pp.

Simojoki H. 1961. *Climatic change and long series of ice observations at Lake Kallavesi*. International Association of Scientific Hydrology, General Assembly of Helsinki 1960, Publication no 54: 20–24.

Solantie R., Drebs A., Hellsten E. & Saurio P. 1996. Lumipeitteen tulo-, lähtö- ja kestoajoista Suomessa talvina 1960/1961–1992/1993 [Timing and duration of snow cover in Finland 1961–1993]. *Meteorological Publications* No. 34 FMI-MET-34, 159 pp. [in Finnish with English summary].

Stigebrandt A. 1987. A Model for the Vertical Circulation of the Baltic Deep Water. *Journal of Physical Oceanography* 17: 1772–1785.

Svensson U. 1978. *A mathematical model of the seasonal thermocline*, Report No 1002. Dep. of Resources Eng. University of Lund. Lund, Sweden, pp. 187.

Thendrup A. (ed.) 1985. *Present practices in the Nordic countries for estimating temperature and temperature changes in lakes and rivers*. Nordic Hydrologic Program, NHP Report No 11, Oslo, 56 pp.

Vassiljev J. Harrison S. P. & Haxeltine A. 1995. Recent lake-level and outflow variations at Lake Viljandi, Estonia: Validation of a coupled lake-catchment modelling scheme for climate change studies. *Journal of Hydrology* 170: 63–77.

Vavrus S. J., Wynne R. H. & Foley J. A. 1996. Measuring the sensitivity of southern Wisconsin lake ice to climate variations and lake depth using a numerical model. *Limnol. Oceanogr.* 41: 822–831.

Vehviläinen B. 1992. Snow cover models in operational watershed forecasting. *Publications of Water and Environment Research Institute* 11, National Board of Waters and the Environment, Finland, Helsinki, 1992, 112 pp.

Vehviläinen B. & Lohvansuu J. 1991. The effects of climate change on discharges and snow cover in Finland. *Hydrological Sciences-Journal* 36: 109–121.

Virta J., Elo A.-R. & Pulkkinen K. 1992. Effect of climatic change on temperature of lakes. In: Kanninen M. & Anttila P. (eds.), *The Finnish Reseach Programme on Climate Change, Progress Report,* Publications of the Academy of Finland 3/92, VAPK-Publishing, Helsinki, pp. 109–114.

Virta J., Elo A.-R. & Pulkkinen K. 1994: Application of lake temperature model for predicting the effect of climatic change. In: Kanninen M. & Heikinheimo P. (eds.), *The Finnish Research Programme on Climate Change, Second Progress Report*, Publications of the Academy of Finland 1/94, Helsinki, pp. 134–139.

Virta J., Elo A.-R. & Pulkkinen K. 1996. Effects of climate changes on the temperature conditions of lake. In: Roos J. (ed.), *The Finnish Reseach Programme on Climate Change, Final Report,* Publications of the Academy of Finland 4/96, Edita, Helsinki, pp. 185–189.

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