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Seasonal Variability of Thermal Regime in a Shallow Ice Covered Lake

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A systematic study was conducted over six years (1994-1999) on a shallow ice covered lake in the Russian Republic of Karelia with the aim of developing better understanding of some physical processes occurring in shallow ice-covered lakes. The average ice-covered period was 182 days while the longest ice-covered period was 193 days. The average lake water temperature at ice formation was 0.5-1.0°C, while the average water temperature just before ice break-up was close to 4°C. The heat flux from water to ice was low during early winter but could increase above 5 Wm-2 (daily average) during the last month before ice break-up. The heat flux from sediment to water was the main source of heat to the water body during early to mid winter being about 2-6 W·m-2 during early winter but decreasing to about 1-2 Wm-2 during early spring.

Introduction

Dynamical processes during winter play an important role for the lake ecosystem. The processes are very different weather the lake is ice covered or not. The water quality is affected by circulation structure, mixing processes, and water temperature. Thus an improved knowledge of physical processes in ice-covered lakes is needed for a better understanding of environmental conditions.

This paper focuses on observations made during six consecutive winters (1994-1999) on the thermal regime in a shallow lake, Lake Vendyurskoe, in Russian

Karelia. Measurement results from one winter has been reported in Malm *et al.* (1997a; 1997b). The aim here is to compare data from different years on factors like ice/snow cover, temperature structure, and heat fluxes during the ice covered period to estimate their variability between years. The study is limited to early and mid-winter conditions (November to April), except regarding ice cover duration.

Lake Vendyurskoe

Lake Vendyurskoe is located in the southern part of the republic of Karelia, Russia (latitude 62°10'N, longitude 33°10'E). The lake has an area of 10.4 km^2, and mean and maximum depth of 5.3 and 13.4 m, respectively. The geometrical dimensions and bottom topography of the lake are given in Fig. 1. Lake Vendyurskoe has several small inflows, and one outflow. The lake hollow has a glacier origin. Its main axis is directed from west to east. The lake has a length and maximum width of 7 and 1.5 km. The bottom sediments consist of sand in the shallow parts (up to 2-3 m depth), and of silt containing organic mud in the upper layer of sediments (with a thickness of 0.4-1.0 m) in the main deeper part of the lake.

Review of Earlier Field Work on Winter Temperature Dynamics in Lake Vendyurskoe

The first study conducted on Lake Vendyurskoe with the aim of investigating the thermal regime of the lake during the ice covered period was carried out between 1978 and 1980. The study entailed the registration of temperature in the upper 1.5 m layer above the sediment in a single vertical profile in the central part of the lake. During the 1978-1979 winter the heat content of the lake at freeze-up was very low, with an average water temperature <0.8°C (Bengtsson *et al.* 1995). The temperature in the bottom sediment was also investigated during this study and data collected showed variation in the temperature with depth of the bottom sediment. The annual amplitude of the sediment temperature decreased with depth, from 12.6°C at 0.5 m to 5.9°C at 1.5 m below the sediment-water interface.

A more detailed study of the temperature regime of the lake was made in 1987-1988 (Bengtsson *et al.* 1995). A thermistor chain (Aanderaa Instruments, Norway) was used to measure water temperature at 3 hours interval from October 1987 until May 1988. The data from the thermistor chain showed that prior to ice formation the bulk water temperature decreased very fast (–0.30-0.35°C d^{-1}), and the mean water temperature dropped to 0.5-0.8°C before freeze-over. The temperature registered from the thermistor chain showed also a continuous increase in water temperature during winter. The rate of increase was highest during the first 2 months of the ice-covered period and was most intensive in the bottom layers.

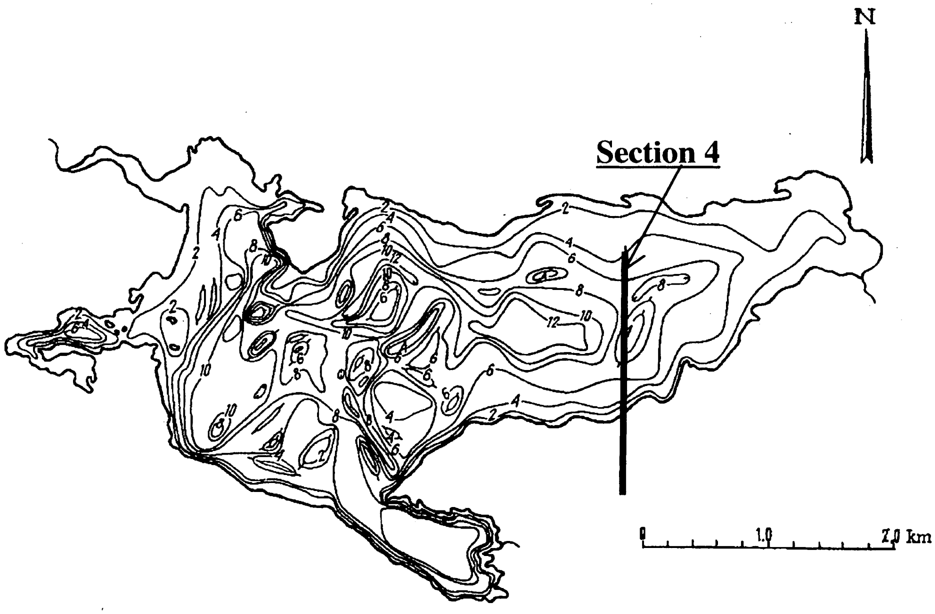

Fig. 1. Depth distribution, geometrical dimensions and location of the cross section with the measurement stations in Lake Vendyurskoe during the winter 1995-1996.

Description of Measurements and Results

During the period 1994 to 1999 measurements were made along cross sections on the shorter axis of the lake (Fig. 1). During the six years of data collection the number of measuring stations varied from year to year. The maximum number of cross sections (6 cross sections) along which observations was made was for the year 1994-1995. The following winter the number of cross sections was reduced to 3, and the winter 1996-1997 reduced down to 1 cross section (cross section No.4).

Measurements focused on the thermal regime including: ice and snow thickness; full vertical profile of temperature and conductivity; detailed temperature and conductivity profiles in the vicinity of the ice; detailed temperature and conductivity profiles at the *sediment-water* interface; and solar radiation (incident, reflected, and under ice surface).

Description of measurements and documentation of observed data has been presented in detail in the reports by Bengtsson *et al.* (1995), Malm *et al.* (1996; 1997) and Maher *et al.* (1999).

Ice and Snow Cover

The extension of the ice coverage period is important for the ecological status of a lake and for the physical processes in the lake. Ice formation is mostly related to meteorological factors; on small freshwater lakes ice formation generally occurs on calm, cold nights. High winds and daytime heating may subsequently break up this cover until calm and cold conditions occur again and the ice cover is formed a second time (Fang *et al.* 1996). Daily average air temperature, wind speed, and volume average water temperature are the main factors that determine the date of ice formation (Gu and Stefan 1990). The growth of the ice cover is governed by the energy balance at the ice-water interface. Ice continues to grow on the lake through most of the winter. The rate of growth in the early winter is rather high and can exceed one centimetre per day.

During the observation years, the ice in Lake Vendyurskoe was generally formed in early/mid-November. This appears to have been the usual time over the last decades, as freeze-up dates during three earlier observation years (1978, 1979, and 1987) were all in early November (see Bengtsson *et al.* 1995). One exception was the winter 1996-97 with ice formation on 12 December. Table 1 shows ice and snow thickness as well as breakup dates and length of ice cover period. The length of the ice-cover period was on average 182 days, *i.e.* about 6 months. This again is consistent with earlier observations in 1978-99, 1979-80, and 1987-88. The date of ice break-up did not vary much; it occurred in mid May, between 8 and 20 May. No cases of temporary ice break-ups were observed during the investigated winters.

Ice thickness was measured in several boreholes throughout the winter. The evolution of the ice thickness during four years is shown in Fig. 2. Early to mid winter, mid winter, and spring values of snow and ice are also given in Table 1. The maximum ice thickness during early winter (Nov-Dec) varied between 19 cm in 1996 to 41 cm in 1995. The ice cover continues to grow until early spring, when the ice cover reaches its maximum. During the six years of investigation, ice thickness during early spring prior to breakup ranged between 64 cm in mid April 1997 to 77 cm in mid April 1996. Maximum snow cover on the ice is usually about 1/3 of the ice thickness during mid winter. One exception is the winter in 1996/1997 when the snow cover was thin (a few cm) but persistent throughout the winter.

The static ice growth is often estimated from Stefan's equation

$$h_s = C\sqrt{S} \tag{1}$$

$$S = \sum_{\text{Daily}} (-T_{\text{air}}) \tag{2}$$

where C is a degree day coefficient that depends on the status of the ice cover. If the ice cover is composed of black ice only, the coefficient is 3.5 cm/(°C day)$^{1/2}$, when snow is present on the ice, the coefficient is about 2.0 cm/(°C day)$^{1/2}$ (Bengtsson 1986). S is the accumulated value of the negative air temperature.

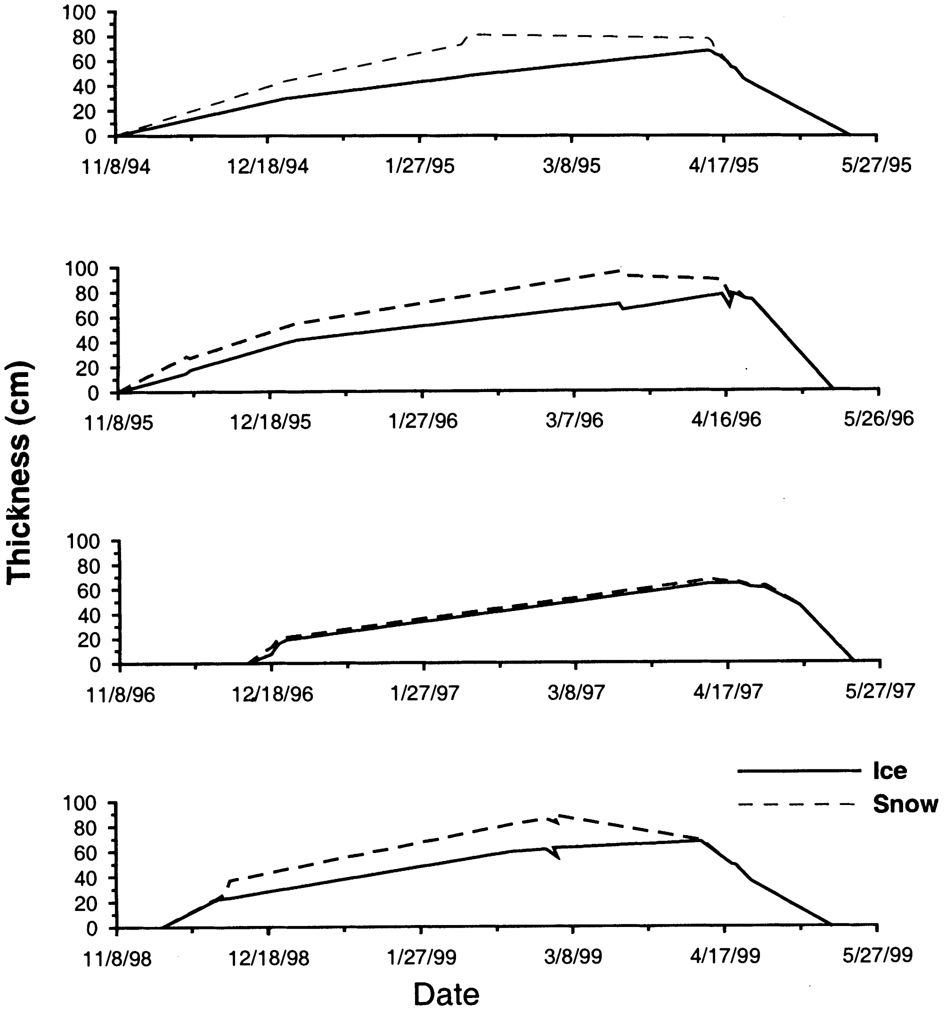

Fig. 2. Ice and snow thickness at Lake Vendyurskoe during 4 years of measurements.

Ice cover was calculated using this approach and compared with measurements (using observed days of ice formation). Good agreement was obtained using $C = 2$ cm/(°C day)$^{1/2}$ as shown in Fig. 3. This particular value of C seems reasonable, since snow was present on the ice for most of the winter as shown in Fig. 2. Since Stefan's equations showed a good agreement with measurements when it comes to maximum average ice thickness, this approach was used to estimate the maximum average ice thickness for years with no measurements. Results are shown in Table 1. The time of ice formation was chosen as 15 November, an approximate average for years with observations. The air temperature data used was collected from Suojarvi

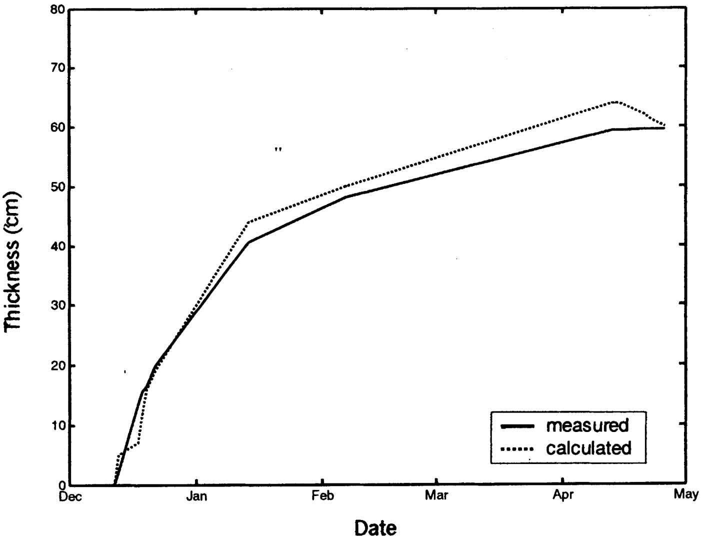

Fig. 3. Measured and calculated (Eqs.(1-2)) ice thickness on Lake Vendyurskoe, winter (1996-97).

Table 1 – Maximum values of ice and snow thicknesses as well as ice cover period length (in brackets) measured in Lake Vendyurskoe.

			Early winter (Nov.-Dec.)		Mid winter (Dec.-Feb.)		Early spring (Feb.-Apr.)	
Year	Freeze up	Break up up	Max ice thick.	Max snow thick. (cm)	Max ice thick. (cm)	Max snow thick. (cm)	Max ice thick. (cm)	Max snow thick. (cm)
1990-91*	–	–	36	–	60	–	66	–
1991-92*	–	–	27	–	52	–	56	–
1992-93*	–	–	33	–	51	–	58	–
1994-95 (193 day)	8 Nov.	20 May	30	14	48	32	68	10
1995-96 (188 day)	11 Nov.	15 May	41	14	65	27	77	12
1996-97 (159 day)	12 Dec.	20 May	19	7	–	–	64	3
1997-98 (–)	–	10 May	–	–	57	24	65	1
1998-99 (188 day)	20 Nov.	8 May	23	14	60	22	67	1
1999-00	–	–	35	–	57	–	61	–

* Calculated values

metrological station (40 km to the west of Lake Vendyurskoe). The model results from these years are consistent with measurement result from observation years. Thus, the ice growth follows a similar pattern from year to year with relatively small variations in average ice thickness between years at a specific time during winter. For instance, for the considered 9 years the maximum ice thickness (obtained in late winter) was between 56 and 77 cm, with an average of 65 cm.

Average Water Temperature

The typical vertical temperature structure in ice covered lakes is a continuous increase downwards from 0°C at the ice-water interface to near 4°C and higher in the bottom layers (Bilello 1968; Ellis *et al.* 1991; Hutchinson 1957; Svensson 1986, Bengtsson *et al.* 1996). The general temperature structure in Lake Vendyurskoe was described in detail by Malm *et al.* (1997 a, b).

The temperature distribution is characterized by minimum heat content during the period of ice formation. For example, as can be seen from Fig. 4, just after freeze over in November 1994, the water temperature was 0.6°C at the surface and near the bottom 1.4°C. The water temperature, especially in bottom layers, increases through-out the winter period due to the heat flux from the sediments to the water. By the end of December the water temperature exceeded 4°C near the bottom.

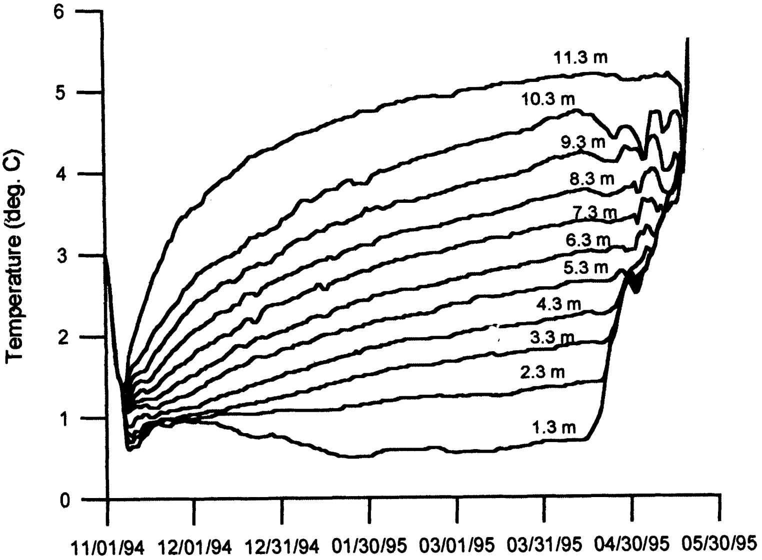

Fig. 4. Thermistor chain recordings in full vertical at a mid lake station during the period 1 November, 1994, to May 21, 1995. The ice formed on November 8, and broke about May 20. The bottom depth is 11.3 m. Depths for thermistors indicated in figure (after Malm *et al.* 1997a).

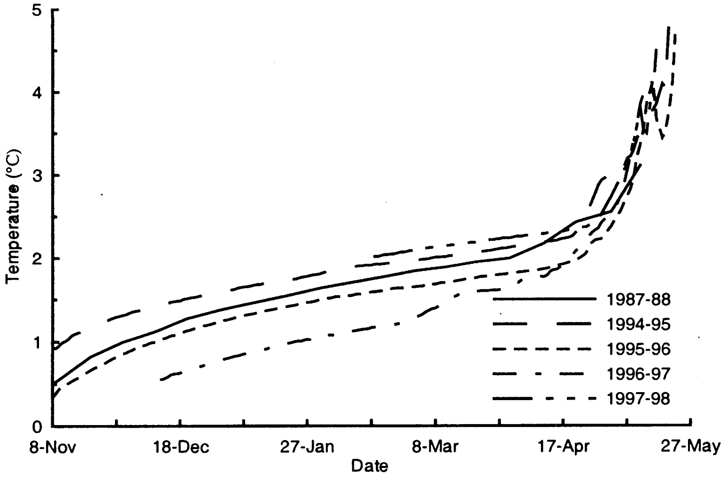

Fig. 5. Average water temperatures in Lake Vendyurskoe during 4 years.

The mean temperature vs. time during winter is shown in Fig. 5 for observation years with thermistor chain recordings in deep-water verticals. The mean temperature development in winter with a continuous temperature growth is very similar year from year with small temperature magnitude differences, except for the winter 1996-97 when freeze-up was one month later than the other years. The average temperature at ice formation was 0.5-1°C for the considered years.

The vertical temperature structure at ice formation and at the beginning of each winter month is shown in Fig. 6. At ice formation there is a neutral to weak temper-

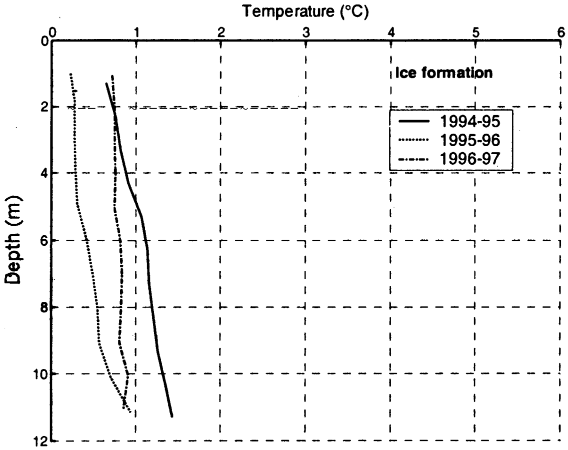

Fig. 6. Vertical Temperature distribution at a deep-water mid lake station, a) at ice formation, b) 1 Dec, c) 1 Feb, d) 1 Apr. For the winter 1998-99 observations were made on slightly different dates – 5 Dec and 3 Mar.

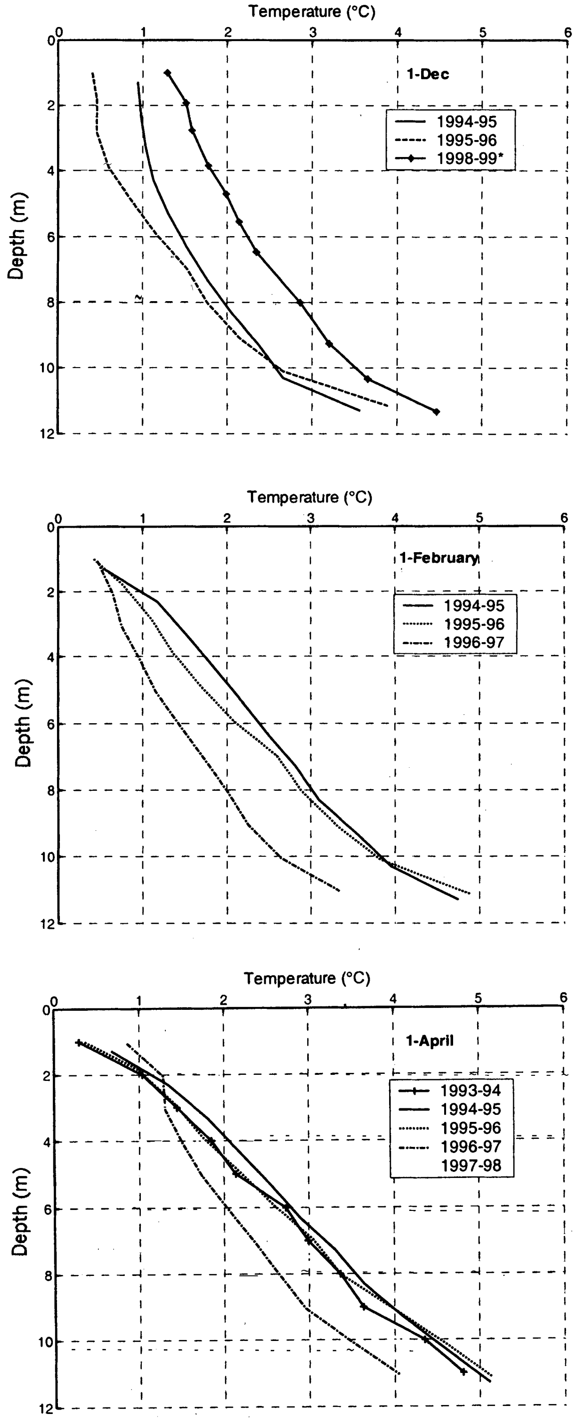
Temperature (°C)
0
1
2
3
4
5
6
Depth (m)
0
2
4
6
8
10
12
1-Dec
1994-95
1995-96
1998-99*
Temperature (°C)
Depth (m)
1-February
1994-95
1995-96
1996-97
Temperature (°C)
Depth (m)
1-April
1993-94
1994-95
1995-96
1996-97
1997-98

Fig. 6. cont.

ature stratification for the considered years. The stratification thereafter rapidly becomes more pronounced, especially in the bottom layers. In April the temperature distribution is almost linear with 0°C just below the ice to above 4°C in the deep waters of the lake. Water temperatures above 4°C (the temperature of maximum density) are normally found in the bottom layers in late winter. This can be explained by the comparatively high salt content at the bottom layers (Malm 1997 a).

The temperature development from ice formation to early April is the same year from year with only small magnitude differences. One exception is the winter 1996-97 when the late ice formation delayed the temperature development, leading to comparatively lower temperatures. The development pattern is, however, the same as observed in other years.

In early and mid winter in 1994-95, Malm *et al.* (1997a) concluded that the isotherms are horizontal, *i.e.* the horizontal temperature variations are very small. This observation was confirmed to be valid for all the investigated years. Malm *et al.* (1997a) also showed that bottom temperatures above 4°C (the temperature of maximum density) is possible due to a with time increased salt content in the bottom layers, ensuring a stable density structure and hydrodynamic stability.

Heat Fluxes at the Ice-water Interface

In lakes with no significant through flow there are two main sources for heating the water body during the ice covered period; heat conduction from bottom sediment and solar radiation that penetrates the ice cover. Heat can leave the lake water since there is a conductive and convective heat flux from water to ice.

Bengtsson and Svensson (1996) determined the heat flux from water to ice and reported a value of 1 Wm^{-2} as mid-winter average for eight Swedish lakes. They found that the heat flux increases in spring when the ice is free from snow and solar radiation can penetrate the ice. Heat flux from water to ice in Ryan Lake, USA, was estimated by Ellis *et al.* (1991) during mid-winter to be 2.8 Wm^{-2}. Gu and Stefan (1990) made numerical calculations for Lake Calhoun, USA, and estimated a maximum heat flux from water to ice at freeze-up (4 Wm^{-2}). From then on they computed a continuous decrease (down to 1 Wm^{-2}) until solar radiation through the ice became important.

The amount of solar radiation that penetrates water depends on snow thickness, ice thickness and characteristics, and radiation intensity. When the snow layer is not very thin, the penetration of solar radiation to the water is negligible. When there is none or only little snow on the ice, heating due to solar radiation is significant. The average rate of penetration during such conditions for two lakes in southern Sweden for the period February – April was estimated by Bengtsson and Svensson (1996) to be about 10 Wm^{-2}. The ice thickness ranged from 20 to 50 cm.

The penetration of solar radiation to the lake water in early and mid winter in

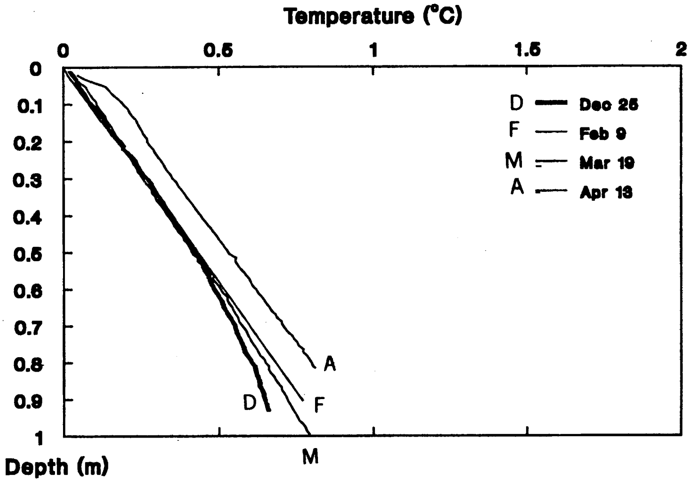

Fig. 7. Vertical temperature structure in the vicinity of the ice at a midlake station in Lake Vendyurskoe during the winter 1994/95.

Lake Vendyurskoe is, based on the studies made above, negligible most winters due to the presence of a thick snow layer on top of the ice. This was confirmed by a few measurements in November and December 1995 (snow layer about 15 cm thick) with heat flux values below or at the detection level, 0.3 W·m^{-2}. However, solar radiation may have penetrated into the water during the winter 1996/97 since only a thin layer of snow was present on the ice this year; no measurements were made during the early to mid winter season.

The temperature profiles gathered through the years of investigation in Lake Vendyurskoe showed that the temperature gradient under the ice is linear from the ice cover to 10-20 cm below it or more. In early and mid winter the gradient is almost constant, while it increases in early spring when solar radiation penetrates the ice. Near-ice temperature profiles are shown in Fig. 7. The linear temperature profile indicates that the heat transfer to the underside of the ice is mainly due to molecular heat transfer see Malm *et al.* (1997b).

The same approach as used by Bengtsson and Svensson (1996) is used here for Lake Vendyurskoe

$$Q_{wi} \equiv - \lambda \frac{\partial T}{\partial z} \tag{3}$$

where T is temperature, and z is vertical coordinate from the bottom of the ice. Assuming molecular conditions within a layer of 10 cm under the ice and using molecular value of conductivity of water at 0°C, $\lambda = 0.569$ Wm^{-1} °C^{-1}, heat conducted from water to ice can be calculated. The average heat flux from water to ice for stations along a cross-section of the lake as calculated from three years of measurements is presented in Table 2. The heat conducted from water to ice is relatively

Table 2 – Heat flux from water to ice (W·m^{-2}) in Lake Vendyurskoe. The heat flux data has been calculated from observed temperature gradients near the ice at section 4. No observations of temperature gradients near the ice were made in 1997/98.

Year	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
1993-94	–	–	–	–	–	1.9
1994-95	–	0.7	–	0.7	0.6	1.0
1995-96	0.6	0.5	0.5	0.5	0.6	1.3
1996-97	–	1.6	1.7	1.3	3.9	6.7
1998-99	–	1.3	0.7	0.6	1.1	5.1

stable through early and mid winter. Generally the heat flux values are about 1 Wm^{-2} or less. For one winter (1996/97) the values are higher, between 1-2 Wm^{-2} in December to February and about 4 Wm^{-2} in March. This is most likely due to that the snow cover was thin throughout the winter this year (see Fig. 2) allowing significant amounts of solar radiation to warm the water below the ice. This in turn caused a higher amount of heat to be conducted from water to ice, being especially noticeable in March and April when radiation intensities are higher. This is also reflected in April values for the other years when the snow normally has vanished.

One may thus conclude that if conditions are normal in Lake Vendyurskoe with a thick snow layer on top of the ice in early and midwinter, the heat flux is fairly constant in time and about 1 Wm^{-2} or less. If the precipitation in winter is small and the snow layer is thin, the heat flux is higher.

Sediment Heat Flux

When the water body is almost isolated from the atmosphere during the ice covered period, the amount of heat conducted from sediment to the water body is significant for the thermal budget of the lake. Heat is transferred from water to the lake sediments during summer and released back into water during the winter period (Hutchinson 1957). The release of heat from sediment to water reduces the temperature of the sediment. Thanderz (1973) reported in a study on a Swedish lake, Lake Velen, that while the temperature at the sediment water interface and in the upper 20-30 cm of the sediment continued to increase, the temperature of the deeper layers of the sediment was decreasing. This sediment heat flux is normally the main heat source in early and mid-winter in an ice covered lake (Bengtsson and Svensson 1996).

The temperature profile at the sediment-water interface in Lake Vendyurskoe was measured. The measurements showed two types of temperature profiles at the sediment water interface, one for deep and another for shallow water. Typical profiles of those two types are shown in Fig. 8. The first type of temperature profile, the

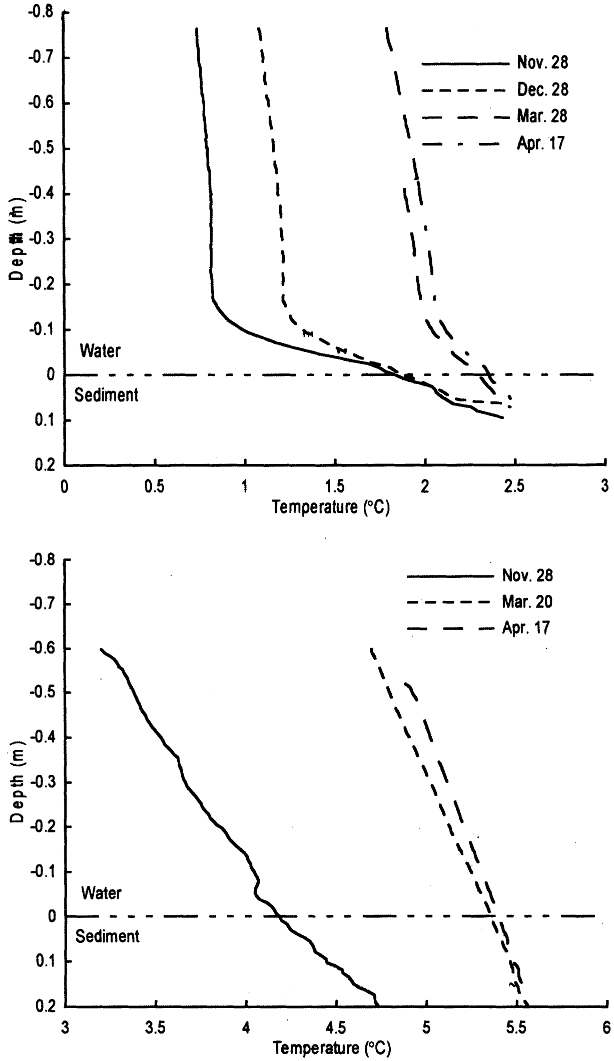

Fig. 8. Vertical temperature structure at the water/sediment interface at a shallow water station (top) and at a deep water station (bottom) in the winter 1996/97.

shallow water profile, is characterized by a strong temperature gradient in the upper layer of the sediment during early winter, and rather constant low temperature in the sediment through the winter, which means a reduced gradient in late winter. The water temperature is rather constant in the water column, slowly decreasing towards the surface. The second type of temperature profile, the deep water profile, rather high temperature in the sediment, 4-6°C, and a linear temperature increase through the upper part of the sediment (between 10 to 20 cm).

The heat flux from sediment to water was calculated using the same method that was used to estimate the heat flux from water to ice, see Eq.(3). The conductivity of the sediments, λ, was estimated from values of porosity and quartz content using a method proposed by Johansen (1975)

$$\lambda = \lambda_w^{\,n} \lambda_s^{\,(1-n)} \tag{4}$$

$$\lambda_s = 7.7^{q} - 2.0^{(1-q)} \tag{5}$$

where λ is conductivity, n is porosity, q is quartz content and the subscripts w and s stands for water and sediment grains, respectively. This approach was tested by Sundberg (1986) for various types of soils and was found to give good agreement with measured conductivity values. The type of sediment, porosity and content of organic material of the upper 10 cm sediment layer were determined the stations along cross-section 4 in Lake Vendyurskoe.

Average sediment heat fluxes from Lake Vendyurskoe are shown in Table 3. The heat flux from sediment to water depends on the bottom depth and time passed after ice formation. The largest heat fluxes are found in early winter, being 2-6 $\mathrm{Wm^{-2}}$ in Nov-Dec. In April the heat flux values have decreased to 1-2 $\mathrm{Wm^{-2}}$. The sediment heat flux development over the winter for a station at a depth of 9.1 m during the winter 1996/97 is illustrated more clearly in Fig. 9. The dependence of bottom depth of the sediment heat flux is more pronounced in early winter, for instance the average sediment heat flux is about 4-5 $\mathrm{Wm^{-2}}$ at depths below 5 m, 3-4 $\mathrm{Wm^{-2}}$ at

Table 3 – Average sediment heat flux ($\mathrm{W{\cdot}m^{-2}}$) for different bottom depths (intervals) and months during winter in Lake Vendyurskoe. No sediment temperature gradients were measured in 1997-98.

Year	Depth (m)	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
	<5	–	–	–	–	–	1.8
1993-94	5-10	–	–	–	–	–	1.3
	>10	–	–	–	–	–	0.7
	<5	–	4.6	–	3.1	2.3	2.3
1994-95	5-10	–	3.1	–	2.0	1.5	1.5
	>10	–	1.6	–	1.3	0.8	0.7
	<5	5.7	3.8	–	–	2.1	1.8
1995-96	5-10	4.1	3.0	–	–	1.7	1.4
	>10	2.9	1.8	–	–	1.0	1.0
	<5	–	4.9	–	–	–	1.9
1996-97	5-10	–	3.6	–	–	–	1.5
	>10	–	2.6	–	–	–	1.0
	<5	–	4.2	–	2.5	–	1.6
1998-99	5-10	–	3.4	–	2.1	–	1.4
	>10	–	1.9	–	1.4	–	1.2

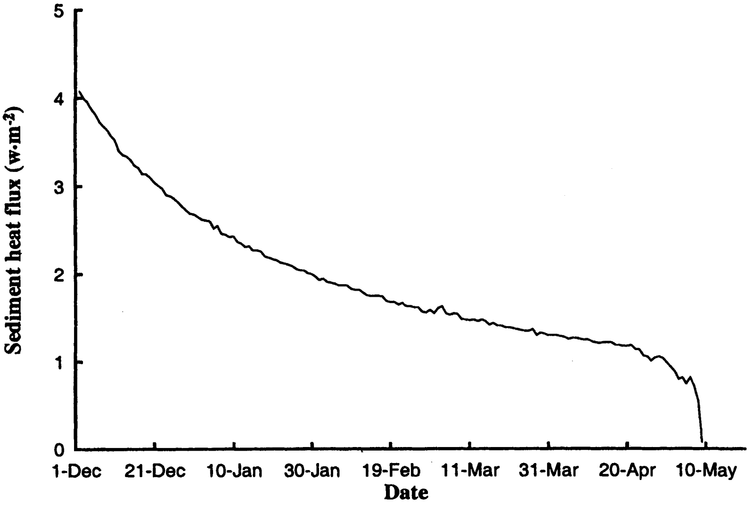

Fig. 9. Heat flux from sediment to water during the winter 1996-97 (station bottom depth 9.1 m) in Lake Vendyurskoe.

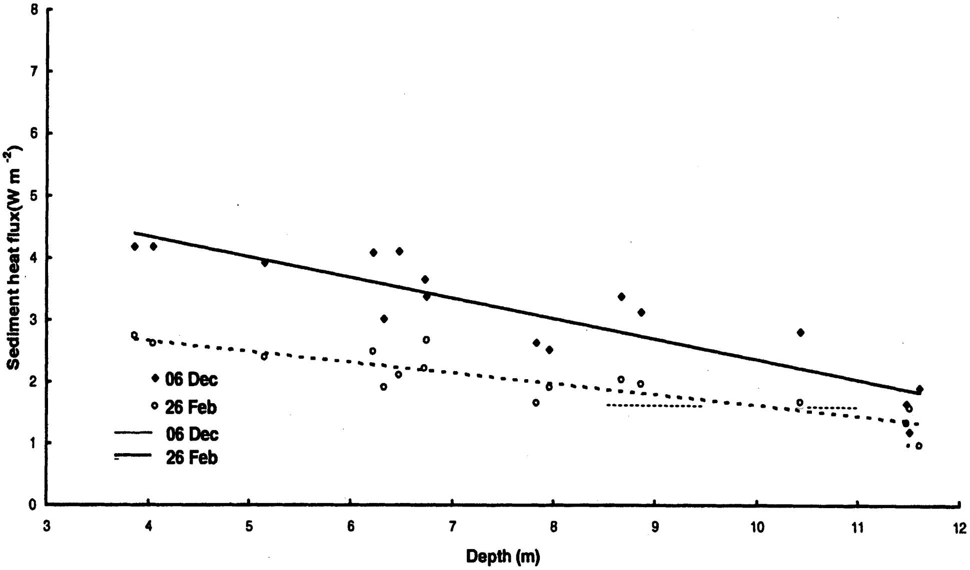

Fig.10. Measures (points) sediment heat flux during the two surveys *versus* bottom depth during winter 1998-99. Linear regression (lines) for each survey, illustrating the bottom depth dependence are also shown.

depths between 5 to 10 m, and 1.5-2.5 Wm^{-2} at depths above 10 m. In April the corresponding values are ~2 Wm^{-2} for bottom depths below 5 m, ~1.5 Wm^{-2} for depths of 5-10 m, and ~1 Wm^{-2} for depths above 10 m. A more transparent picture of the influence of bottom depth on the sediment heat flux is given in Fig. 10. The time dependence and bottom depth dependence follows the same pattern year from year. Only small differences in sediment heat flux magnitude for a certain depth and time during winter are observed between the years. The heat flux decreases continuously after ice formation, rapidly in early winter and slowly in late winter. This characteristic is the same each year.

Conclusion

Data collected during the duration of six years demonstrated similar thermal regimes between winters. A permanent ice cover throughout a 6-month winter characterizes Lake Vendyurskoe. The time of ice freeze-over is normally early to mid November. The maximum ice thickness is 60-80 cm. The average water temperature is low (normally <1°C) and almost uniform at ice formation. The temperature increases continuously during winter, but isotherms are horizontal in. early and mid winter. Water temperatures above 4°C (the temperature of maximum density) are normally found in the bottom layers in late winter. This is possible as the salt content is comparatively high in the bottom layers.

The temperature increase during early and mid-winter is due to heat being released from the sediments to the water. The sediment heat flux is high initially and decreases successively during the winter. Typical values of the sediment heat flux values were 2-6 Wm^{-2} in early winter and 1-2 Wm^{-2} in late winter. The loss of heat from the lake water is solely due to heat being conducted from water to ice. This heat flux is relatively constant in early and mid-winter, about 1 Wm^{-2}. The heat flux from water to ice increases in late winter and can reach considerably higher values (>5 Wm^{-2}) due to vanishing snow cover and increases in solar radiation intensity. The heating due to solar radiation is high when the ice is snow free and dominates the heat input to the lake.

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