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Temperature and Salt Content Regimes in Three Shallow Ice-Covered Lakes

1. Temperature, Salt Content, and Density Structure

J. Malm, A. Terzhevik and L. Bengtsson
Lund University, S-221 00 Lund, Sweden

P. Boyarinov, A. Glinsky, N. Palshin and M. Petrov
Russian Academy of Sciences, 185 003 Petrozavodsk, Russia

A field study on the temperature, salt content, and density regime in three shallow ice-covered Karelian lakes is presented. The measurements show that the heat content increases during the whole ice-covered period. At ice formation a weak stable stratification existed in the lakes, with average temperatures about 1°C. Thereafter, the stability of the stratification gradually increased, mainly due to pronounced temperature increases in the bottom layers. In mid-winter the bottom layer in the deep parts of the lakes obtained temperatures above 4°C. The density stratification in these layers was stable, however, due to higher salt contents (increasing continuously during the winter) in the vicinity of the bottom. The horizontal variations in temperature and salt content were very small, and both parameters can be considered to be horizontally homogeneous.

Under-ice convection was developed in two of the three investigated lakes during the second half of April, when heating due to penetrating solar radiation became apparent. Although no under-ice convection in the conventional sense occurred in the third lake (Uros), interior convection developed when the temperature exceeded 4°C (the temperature of maximum density) there. The absence of under-ice convection in Lake Uros is most likely due to the higher vertical temperature gradient in the lake before spring heating and smaller extinction coefficient than in the other two lakes.

Introduction

Although lakes in Europe, Northern Asia and North America (and thus most of the lakes of the world) are ice-covered for several months of the year, little research has been devoted to the winter regime in temperate lakes. The temperature structure in shallow ice-covered lakes is characterized by a continuous increase from 0°C at the ice-water interface up to 4°C or higher in the bottom layers in the deep parts of the lake (Bibello 1968; Ellis *et al.* 1991; Hutchinson 1957; Svensson 1987). Although the thermal structure in the bottom layers with temperatures exceeding 4°C (the temperature of maximum density for freshwater) indicates hydrodynamic instability, this is not the case because of increasing salt concentrations in these layers (Bengtsson *et al.* 1995).

When the lake is ice-covered, it is almost insulated from the atmosphere. Therefore, the heat content of the lake changes rather little after it has become ice-covered. Temperature increases throughout the main mass of water after freeze-over have been recorded by several investigators since Harrison (1863), see for instance, Simojoki (1940); Thanderz (1973); Svensson (1987). Yoshimura (1937) gives three causes for the warming: solar radiation, heat flow through the bottom sediments and inflow of warm water. The solar radiation through the ice is the dominant heat source in late winter, but much less significant in mid-winter, especially if the ice is covered with snow. The heat flux from the bottom sediments dominates in the shallow parts. Although it is small, 1-4 W m^{-2}, and decreases through the winter, it is sufficiently large to increase the heat content of lakes in the course of the winter unless the river inflow is very large. Heat is lost with the outflow and as a conductive heat flux from the water to the underside of the ice. The latter is usually lower than the sediment heat flux during the main part of the winter, but can be much higher during the convective period in late winter/early spring (Bengtsson and Svensson 1996; Bengtsson *et al.* 1995).

Previous field investigations of the temperature field in ice-covered lakes have mostly been restricted to a few verticals, often with a course spatial resolution. Furthermore, the salt concentration distribution and its influence on the density field has usually not been considered. To extend the information from earlier investigations on thermal and salt content regime in ice-covered lakes, a field study was carried out during the winter 1994/1995 in three small and shallow lakes in Karelia, Russia. The ice-covered period normally extends over six months (November to May) in these lakes and is characterized by small river in/outflows (with a negligible effect on the heat balance during winter), and a continuous heat content increase. In early and mid-winter (November to mid-April), the heat content increase is mainly caused by heat transfer from bottom sediments to water. During late winter/early spring (mid-April to May) the snow cover on top of the ice disappears, and penetrating solar radiation determines the temperature development in the lakes (Malm *et al.* 1996).

The general objective of the study was to obtain detailed information on the temperature and salt content structure, both vertically and horizontally, covering the whole ice-covered period. Special attention was devoted to the layers in the vicinity of the solid boundaries (underside of the ice cover and sediment-water interface). Besides that, data on temperature and salt concentration gradients can give valuable information on the heat and mass fluxes to the lake, since the thermal and mass forcing at the boundaries are likely to induce more pronounced vertical temperature and salt content changes there, compared to the lake interior. Attention was also focussed on conditions for onset of convection and on the convection development during the spring heating period. If under-ice develops, it is the most effective mixing process experienced during winter, leading to a redistribution of substances within the lake, which will be of importance for the development of the lake ecosystem after ice breakup. Relatively little temperature data have been presented from the convection period in shallow lakes, and information resolving the upper boundary layer and the "thermocline" (developed by penetrative convection) is missing. Therefore, measurements with fine depth resolution were organized within the field study, combined with continuous registrations of solar radiation at the underside of the ice.

The text below covers general information about the three lakes, description of measurements, and measurement results. The presentation of measurement results is divided into two parts, one covering early and mid-winter (November to mid-April) and one focussing on late winter/early spring (mid-April to May). This separation is mainly due to the different main heat sources during the two periods. Analysis of boundary heat fluxes as well as horizontal heat fluxes within the lake is given in another article by Malm *et al.* (1997), this issue.

General Information About the Three Investigated Lakes

Lakes Uros, Rindozero, and Vendyurskoe are located in the southern part of the Republic of Karelia, Russia (latitude 62°10'-62°20'N; longitude 33°10'-33°20'E). They all lie within the same watershed, which has an area of 82.8 km^2. The main characteristics of the lakes are presented in Table 1. The three lakes are relatively small (areas of 10 km^2 or less) and shallow (average depths of 5 m or less). Lakes Vendyurskoe and Rindozero are supplied by waters of three inflows each. The watershed of Lake Vendyurskoe is almost twice that of Lake Rindozero, but its residence time (time for exchange of the lake water volume) is 5.3 times higher because of the larger dimension of this lake. According to Bengtsson and Svensson (1996), the heat loss associated with throughflow during winter is negligible compared to other heat fluxes if the hydraulic load, defined as the flow rate divided by the lake's surface area, is 10^{-7} m sec^{-1} or less. Taking the annual average flow rate (Table 1) to be typical also for the ice-covered period, the hydraulic load is of the order of 10^{-7} m sec^{-1} or less in all three lakes. Therefore, the influence of river throughflow on the heat budget of the lakes during the ice-covered period is negligible.

In Lake Uros, river inflow has a negligible influence on the renewal time. Instead, precipitation and ground waters are the main sources of water supply throughout the year. Also from an ecological point of view, Lake Uros is different, being an oligotrophic lake, while the other two are mesotrophic lakes. Consequently, the water transparency is higher, and it is possible to see the bottom at almost any point in Lake Uros. Corresponding typical Secchi disc readings in Lakes Vendyurskoe and Rindozero are 3-4 m and 1.5-2 m, respectively.

Table 1 – Main characteristics of the three investigated lakes (Litinskaya and Polyakov 1975)

	Uros	Rindozero	Vendyurskoe
Area (km^2)	4.3	1.8	10.4
Max depth (m)	9.5	9.5	13.4
Mean depth (m)	2.9	3.9	5.3
Volume ($10^6\ m^3$)	12.2	7.9	54.8
Drainage basin area (km^2)	9.9	43.6	82.8
Annual inflow/outflow rate ($m^3 \cdot sec^{-1}$)	0.1	0.4	0.6
Water residence time (years)	3	0.6	3

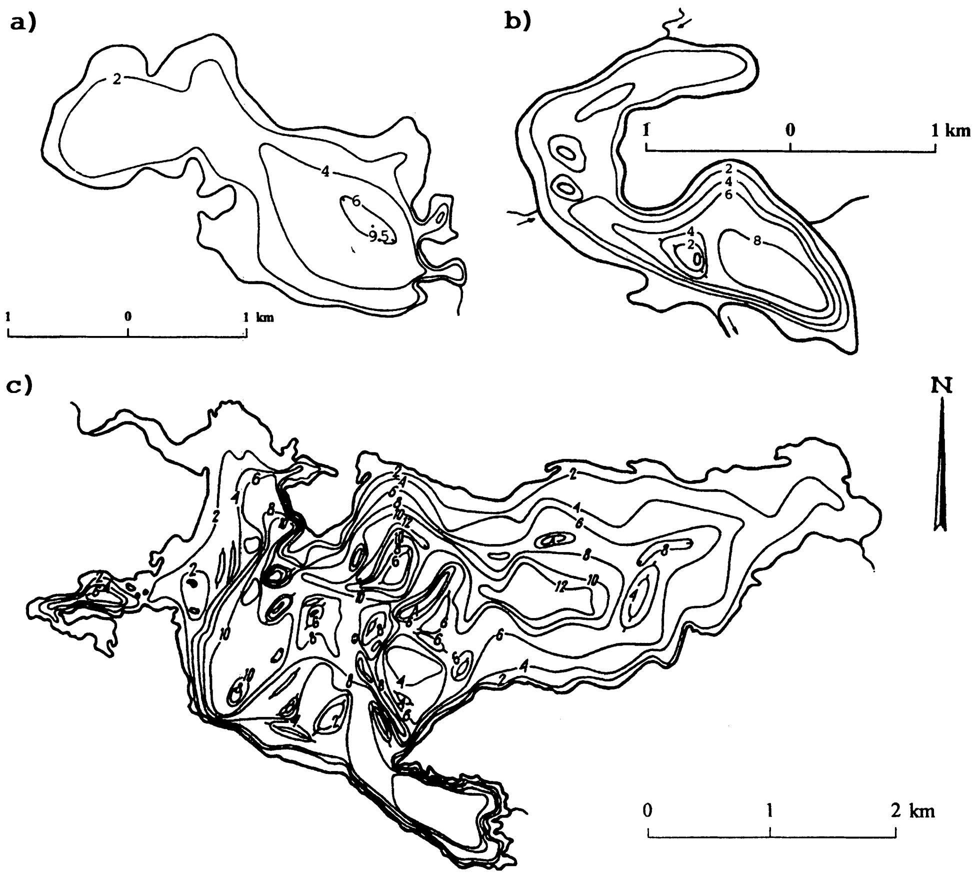


Fig. 1. Depth distribution and geometrical dimensions of Lakes Uros – **a**, Rindozero – **b**, and Vendyurskoe – **c**.

Lake Uros

Lake Uros is a shallow basin, where the major part has a depth of about 2-4 m, see Fig. 1a. The deepest hollow, with a maximum depth of 9.5 m and an area less than 100 m^2, is located in the eastern part of the lake. The bottom sediments consist of white sand up to 2 m depth in the eastern shallower part (14% of the lake's area), and of brown and dark-brown silt in the central and western parts (65% of the lake's area). According to the grain size composition, fine silts (particle size of 0.01-0.05 mm) dominate. The thickness of the silt sediments is more than 1.2 m. All silt sediments have a high organic content.

Lake Rindozero

The drainage basin of Lake Rindozero has an area of 43.6 km^2, mostly occupied by forest (60%), but also with swamps (19%) in the lower parts. The water residence time is 7.5 months, that is several times smaller than for Lakes Uros and Vendyurskoe. However, in winter the river in/outflow is small.

The bottom topography of Lake Rindozero is shown in Fig. 1b. The northern part is shallow, with depths of 2-4 m, while the southern part has depths exceeding 9 m. The shallow part of the lake (less than 2 m depth) is characterized by sand sediments (covering more than 18% of the lake's area). The main lake sediments are fine silts of dark-brown color (76% of the lake's area). The finest silts are located within the deep hollow area. The thickness of the silt sediments is more than 1 m.

Lake Vendyurskoe

Lake Vendyurskoe has three small inflows, and one outlet. The lake hollow has a glacier origin, with its main axis directed from west to east. The lake is 7 km long with a maximum width of 1.5 km. The maximum and mean depth are 13.4 and 5.3 m, respectively. The depth distribution in the lake is shown in Fig. 1c. The bottom sediments consist of sand in the shallow parts (less than to 2-3 m depth), and of silt containing organic mud in the upper layer of the sediments (with a thickness of 0.4-1.0 m) in the main deeper part of the lake.

Description of Measurements

Measurements were made from the ice along six cross-sections in Lake Vendyurskoe (in total 49 measurement stations), at two stations in Lake Uros, and at three stations in Lake Rindozero, see Fig. 2. In total four surveys were made during the winter 1994/1995: in December, February, March, and April. The measurements during each survey included (capacities of the measurement devices are given in Table 2),

1) full vertical profiles of temperature and conductivity registered from a hole in the ice at all stations. The devices used were a TCD (Temperature-Conductivity-Depth) profiler, having a vertical depth resolution of 5 cm, and a digital TC me-

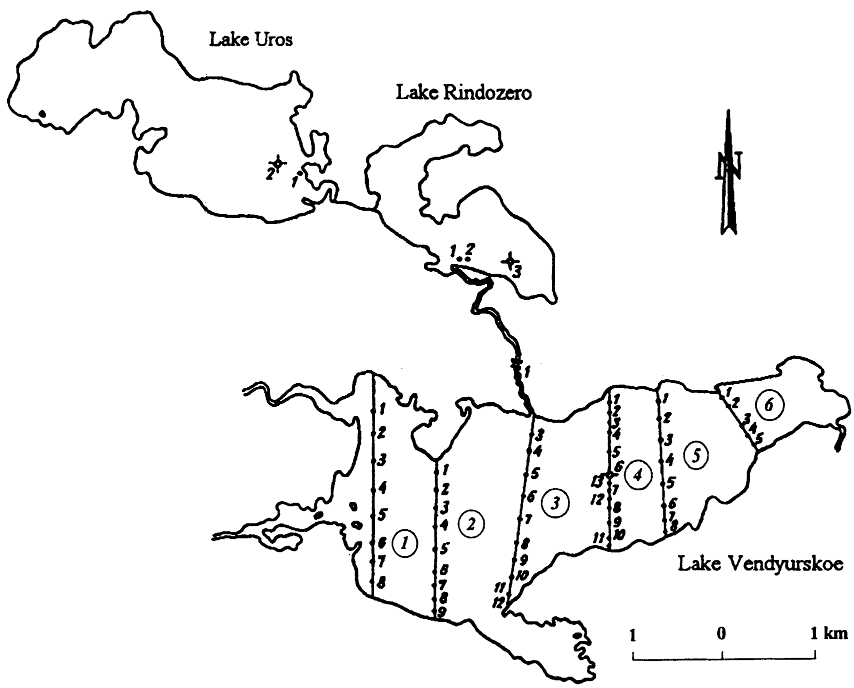


Fig. 2. Location of measurement stations in the three investigated lakes. Stations marked with a cross represent a location of the thermistor chains.

ter (used during the second survey in Lake Vendyurskoe), where readings were taken each half a metre;

2) profiles of temperature and conductivity in the vicinity of the ice at one cross-section (section 4) in Lake Vendyurskoe and at the stations in Lake Uros and Lake Rindozero. The registrations were made with the TCD profiler, mounted on a special construction (described by Bengtsson *et al.* 1995), which allowed readings to be taken at 8 mm intervals for a 1 m layer below the ice and at a distance of 1 m away from the hole in the ice;
3) registrations of temperature gradients in the upper 10 cm of the sediments at the stations in Lakes Uros and Rindozero, and at two cross-sections (section 4 – all surveys, section 5 – survey 3 and 4) in Lake Vendyurskoe. The specially designed measurement probe, see Bengtsson *et al.* 1995 for a thorough description, includes two thermistors, spaced 10 cm apart, and a circular disc for detection of the sediment-water interface;
4) profiles of temperature and conductivity at the sediment-water interface (fourth survey) at the stations along three cross-sections (sections 4, 5, and 6) in Lake Vendyurskoe. The measurement probe included an optical sensor for detection of the sediment-water interface and was lowered using a micro-winch, allowing for a spatial resolution of 8 mm between registrations;

Table 2 – Measuring capacities of the devices used in the field campaign. The temperature profile recorder and pyranometers were developed by Aanderaa Instruments, Norway. All other instruments have been developed at the Northern Water Problem Institute, Petrozavodsk, Russia, and are described in a report by Malm *et al.* (1996).

Device	Parameter	Range	Accuracy	Resolution	Response time
Thermistor chain, TR-1	Temperature – 11 channels (°C)	-2.46..+21.48	±0.15	0.02	3.5 min
TCD profiler	Temperature (°C)	0..25	±0.05	0.003	0.1 s
	Conductivity	10..50	±3%	0.2%	0.1 s
	($\mu S \cdot cm^{-1}$)	10..1000	±10%	3%	0.1 s
	Depth (m)	0..100	0.05+2%	0.05	0.1 s
	Depth for under-ice probe (m)	0..1.5	0.02+2%	0.008	
	Depth for bottom probe (m)	-1..0.2	0.01+10%	0.008	
Digital TC meter	Temperature (°C)	-2..+30	±0.05	0.01	1 s
	Conductivity ($\mu S\ cm^{-1}$)	0..70	±1%	0.03% FS	1 s
Bottom temperature gradient meter	Temperature gradient (°C m^{-1}), 3 ranges	-0.3..+0.3, -1..+1, -3..+3	0.03+2% FS	1% FS	10 min
Pyranometers	Solar radiation ($W\ m^{-2}$)				
1)Normal		0..1000	1+10%	1	5 min
2)Submergible		0..200	0.3+20%	0.2	5 min

5) determinations of ice and snow thickness at all stations;
6) continuous registrations of incident and reflected solar radiation and of the amount of solar radiation that penetrated through the ice in the middle of Lake Vendyurskoe (fourth survey, station 4-3).

Before the ice cover was formed, two thermistor chains were installed in the deep parts of Lake Vendyurskoe (station 4-6, bottom depth 11.3 m) and Lake Rindozero (station 3, bottom depth 9.0 m). The sensors were positioned on depths 1.3, 2.3, 3.3, 4.3, 5.3, 6.3, 7.3, 8.3, 9.3, 10.3, and 11.3 m, and 1.5, 2.5, 3.5, 4.5, 5.5, 6.5, 7.5, 8.5, and 9.0 m, respectively, with registrations each third hour during the whole ice-covered period. In Lake Uros a thermistor chain was installed on station 2 (bottom depth 5.5 m) after the ice cover formation for the period December 25, 1994 – May 25, 1995, with sensor positions on depths 1.0, 1.35, 1.7, 2.05, 2.4, 2.75, 3.1, 3.45, 3.8, 4.5, and 5.2 m, with temperature registrations each hour. The water and sediments of

Table 3 – Dates of temperature profile measurements (full – A; under-ice – B; sediment-water interface – C; temperature gradient in the upper 10 cm of the sediments – D) and type of equipment used (1 stands for TCD profiler; 2 for digital TC meter; 3 for under-ice TCD profiler; 4 for bottom TCD profiler; and 5 for bottom temperature gradient meter) at the measurement stations in the three lakes for each survey during the 1994-1995 field campaign.

Survey	Section	Station	Type of measurements	Date of measurements	Type of equipment
			Lake Vendyurskoe		
1	1	1-8	A	21 Dec	1
	2	1-9	A	22 Dec	1
	3	3-12	A	22-23 Dec	1
	4	1-10	A, B, D	23, 25 Dec	1, 3, 5
	5	1-8	A	21 Dec	1
	6	1-5	A	20 Dec	1
2	1	1-8	A	9 Feb	2
	2	1-9	A	9 Feb	2
	3	3-12	A	9, 12 Feb	2
	4	1-10	A, B, D	7-8, 12 Feb	2, 3, 5
	5	1-8	A	10 Feb	2
	6	1-5	A	10 Feb	2
3	1	1-8	A	14 Mar	1
	2	1-9	A	15 Mar	1
	3	3-12	A	16 Mar	1
	4	1-10	A, B, D	19 Mar	1, 3, 5
	5	1-8	A, D	16 Mar	1, 5
	6	1-5	A	15 Mar	1
4	3	3-12	A	15 Apr	1
	4	1-10	A, B, D	13 Apr	1, 3, 5
	4	3-13	C	16 Apr	4
	4	3, 6	A, B, C	16-23 Apr	1, 3, 4
	4	1-10	A	22 Apr	1
	5	1-8	A, C, D	14 Apr	1, 4, 5
	6	1-5	A, C	16 Apr	1, 4
			Lake Uros		
1	10	1-2	A, B, D	24 Dec	1, 3, 5
2	10	1-2	A, B, D	10 Feb	1, 3, 5
3	10	1-2	A, B, D	17 Mar	1, 3, 5
4	10	1-2	A, B, D	19 Apr	1, 3, 5
			Lake Rindozero		
1	20	1-3	A, B, D	24 Dec	1, 3, 5
2	20	1-3	A, B, D	10 Feb	1, 3, 5
3	20	1-3	A, B, D	17 Mar	1, 3, 5
4	20	1-3	A, B, D	19 Apr	1, 3, 5

the lakes were characterized by measuring the extinction coefficient for water and determining sediment type, porosity, and organic content. The dates and locations for each measurement type and equipment used are summarized in Table 3.

To obtain values on salt content from the conductivity readings, the following relation was used

$$S = 0.821\kappa_{18} \quad (1)$$

where S (mg l^{-1}) is salt content, and k_{18} (μS cm^{-1}) is the measured water conductivity related to 18°C. This relation was determined by the Northern Water Problem Institute in Petrozavodsk, Russia, (unpublished report) for the considered lakes. The density as a function of water temperature and salt content was then calculated using the Chen and Millero (1986) formula.

When profiling the full water depth from ice cover down to bottom, the measured salt content and density values up to 20 cm above the bottom were removed. Since the upper layer of the sediments most often has a high water content, it is difficult to distinguish the sediments from the water itself unless as in the detailed water-sediment interface measurement special equipment is used. The salt content increases sharply through the sediment-water interface, but no such drastic changes in temperature gradients was observed. Therefore, the temperature data very close to the bottom are also shown for all measurement stations.

Measurement Results – Early and Mid-winter

Ice and Snow Thickness

Measurements of ice and snow thickness were made at all stations in the three lakes during the four surveys. The data are summarized in Table 4.

The ice cover was formed on November 8 in all three lakes, and grew steadily throughout the winter until the middle of April, when a maximum thickness of about 65 cm was reached. The measured ice thicknesses in Lake Uros and Lake Rindozero during the fourth survey (April 19) indicate the first stage of ice melting. The spatial variability of the ice thickness is relatively small, with a standard deviation of a few cm.

The lakes were covered with snow before the first survey in the end of December (~15 cm snow depth), and this snow cover remained until the middle of April. The biggest snow thicknesses (~30-40 cm) were measured during the second survey in the middle of February. The spatial variability of snow cover thickness is as for ice a few cm, but comparatively larger relative the average thickness – about 30%.

There are no significant differences in snow and ice thickness between the three lakes, which is also to be expected, since the lakes are all located within a few kilometres of each other, and thus the climatic conditions are similar. An interesting observation based on Table 4, is that a layer of water was located on top of the ice

Table 4 – Snow thickness (h_s), ice thickness (h_i), and water level in drilled holes in the ice measured from the underside of the ice (h_w), in Lake Vendyurskoe (49 stations), Uros (2 stations), and Rindozero (3 stations), during the four surveys in winter 1994/1995. (Avg stands for Average, and Std for Standard deviation)

Lake	Survey	h_s (cm)		h_i (cm)		h_w (cm)
		Avg	Std	Avg	Std	Avg
Vendyurskoe	1 (Dec 20-23)	16	4	29	2	30
	2 (Feb 7-12)	27	9	50	6	58
	3 (Mar 14-19)	8	2	67	3	64
	4 (Apr 13-16)	6	4	70	3	66
Uros	1 (Dec 24)	18	-	32	-	33
	2 (Feb 10)	40	-	52	-	56
	3 (Mar 17)	8	-	67	-	64
	4 (Apr 19)	0	-	64	-	58
Rindozero	1 (Dec 25)	15	-	28	-	33
	2 (Feb 10)	40	-	48	-	52
	3 (Mar 17)	7	-	67	-	64
	4 (Apr 19)	0	-	58	-	54

Note: when $h_w > h_i$, this indicates a layer of water located on top of the ice.

during the first two surveys (*i.e.* $h_w > h_i$), and thus the base of the snow layer was saturated with water. This occurs because the combined weight of snow and ice is larger than the weight of water with a thickness corresponding to that of the ice. Therefore, during this part of the winter, ice was formed mainly on the upper side of the ice cover. This was also the cause for a layered ice structure that developed during the winter, with black "crystalline" ice in the lower part and white "snowy" ice on the top. A similar kind of layered ice structure has also been observed in other lakes (see for instance, Likens *et al.* 1985).

Thermistor Chain Recordings

The temperature in verticals registered by thermistor chains in the deep parts of the three lakes during the winter are shown in Figs. 3-5. In Lake Vendyurskoe and Lake Rindozero the day of minimum average temperature (~1°C) corresponds to the day of ice formation, November 8. The thermistor chain in Lake Uros was installed on December 25, and therefore no such data exist for this lake. The temperature then increased steadily throughout the winter (except close to the ice), rapidly in the beginning and more slowly in mid-winter. In early winter, the main temperature increase is located to the vicinity of the bottom. For instance, the bottom temperature exceeded 4°C on December 16 in Lake Vendyurskoe and on January 1 in Lake Rindozero. Thus, it seems that bottom heating due to heat transfer from the bottom sediments is most intense in early winter. In mid-winter the temperature increase is more homo-

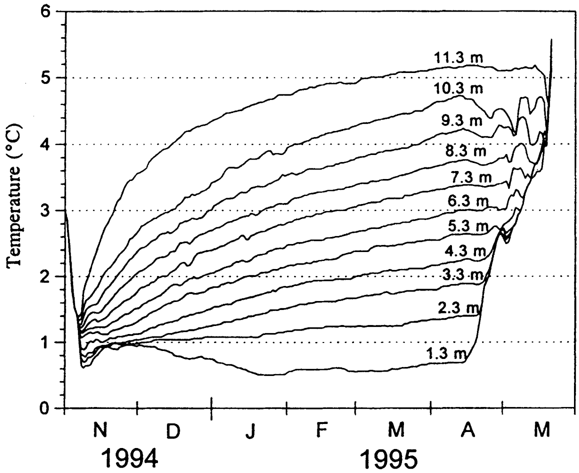


Fig. 3. Thermistor chain recordings in a vertical in the deep part of Lake Vendyurskoe during the period October 24, 1994, to May 24, 1995. The ice formed on November 8, and broke about May 20. The bottom depth is 11.3 m.

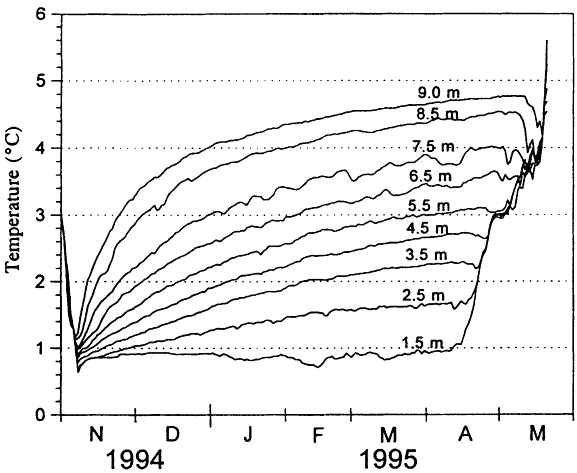


Fig. 4. Thermistor chain recordings in a vertical in the deep part of Lake Rindozero during the period October 26, 1994, to May 25, 1995. The ice formed on November 8, and broke about May 20. The bottom depth is 9.0 m.

geneous throughout the water column. The average temperature is higher in Lake Uros than in the other two lakes, which is reasonable since Lake Uros is shallower than the other two lakes, and thus the heat transferred from the sediments to the water warms a comparatively smaller volume. Although the temperature in the bottom layer in all three lakes is higher than 4°C (the temperature of maximum density) during the main part of the winter, the density stratification is stable, since, as shown in the next section, the salt content is high near the lake bottom.

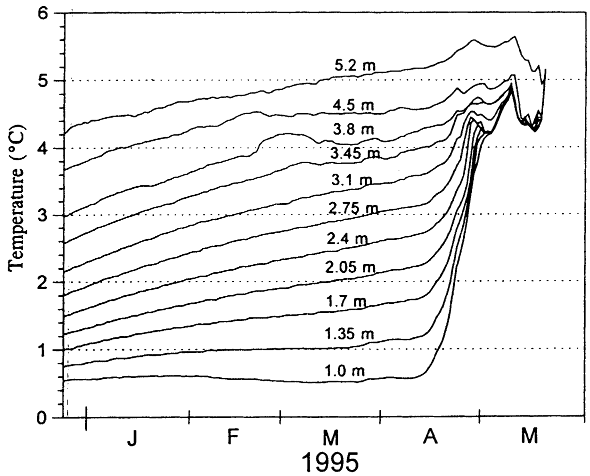


Fig. 5. Thermistor chain recordings in a vertical in the deep part of Lake Uros during the period December 25, 1994, to May 25, 1995. The ice break-up occurred about May 20. The bottom depth is 5.5 m.

The heat content increases, assuming horizontal homogeneity, during early and mid-winter (November 8 to April 15 – Vendyurskoe and Rindozero, December 24 to April 15 – Uros) are 211, 31, and 47 TJ for Lakes Vendyurskoe, Rindozero, and Uros, respectively. The corresponding average rates of heat content change for a water column in the three lakes are 1.5, 1.3, and 1.1 W m^{-2}. Therefore the boundary heat fluxes during early and mid-winter should be small, in the order of 1 W m^{-2}.

Full Vertical Profiles of Temperature, Salt Content, and Density

To obtain information about both the horizontal and vertical distribution of the temperature, salt content and density, measurements were made at a number of stations in all three lakes during the four surveys. The registered data for three stations in the deep parts of Lakes Vendyurskoe, Rindozero, and Uros, positioned at the thermistor chain locations, are given in Figs. 6-8 (the data from all other stations in the lakes have been presented in a report by Malm *et al.* 1996). In the temperature profiles from the fourth survey (April 19) in Lakes Rindozero and Uros, heating due to penetrating solar radiation can be distinguished. In Lake Uros this heat is distributed rather homogeneously in the first metres below the ice cover, while the heat input in Lake Rindozero is concentrated very near the vicinity of the ice. The salt concentrations in the bulk of the water column do not show any large changes within each lake. The corresponding typical concentrations are 20, 18, and 11 mg l^{-1} for Lakes Vendyurskoe, Rindozero, and Uros, respectively. Thus, the chemical composition of the water in Lake Uros is slightly different compared to the other two lakes, with only half the amount of salts. Near the bottom, there is, in general, a salt content increase with depth, and also with time. This is especially pronounced in the deeper

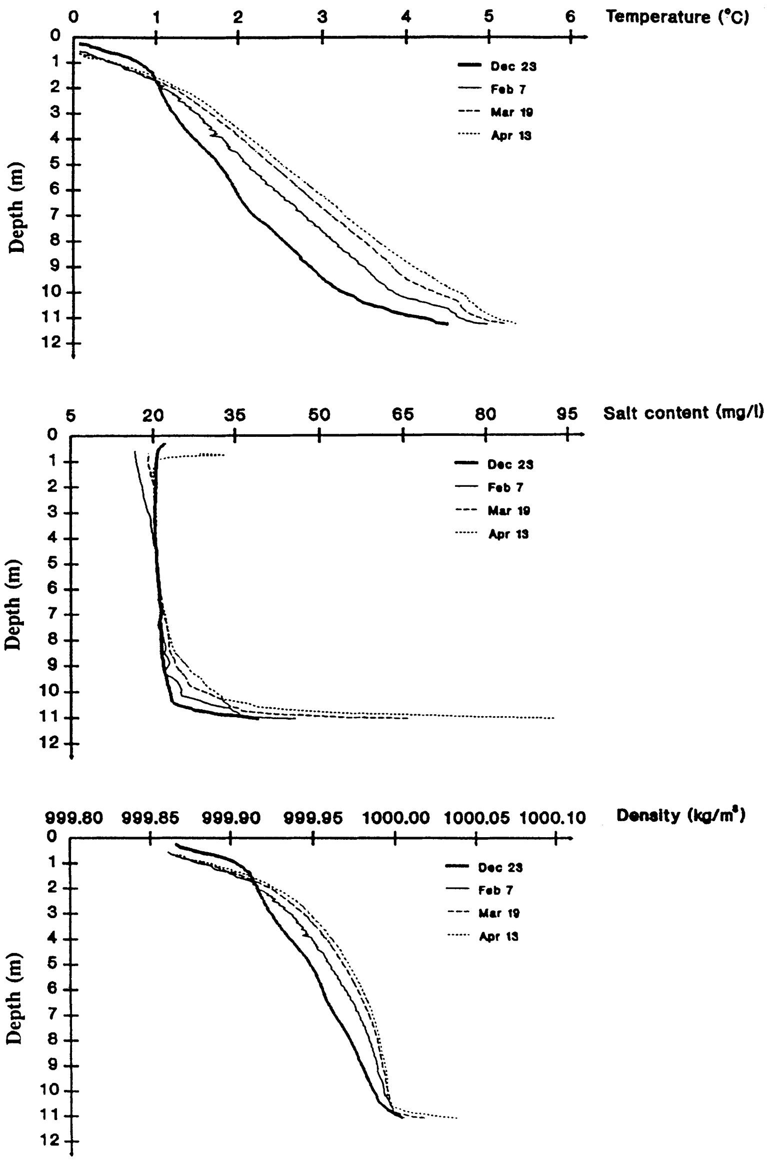


Fig. 6. Vertical temperature, salt content, and density structure recorded during the four surveys in Lake Vendyurskoe at station 4-6.

parts of each lake, with concentrations up to 100 mg l^{-1} in Lakes Vendyurskoe and Rindozero. The high salt content close to the bottom ensures a stable density stratification, although the bottom temperature is above 4°C. In Lake Uros the stratification is approximately neutral.

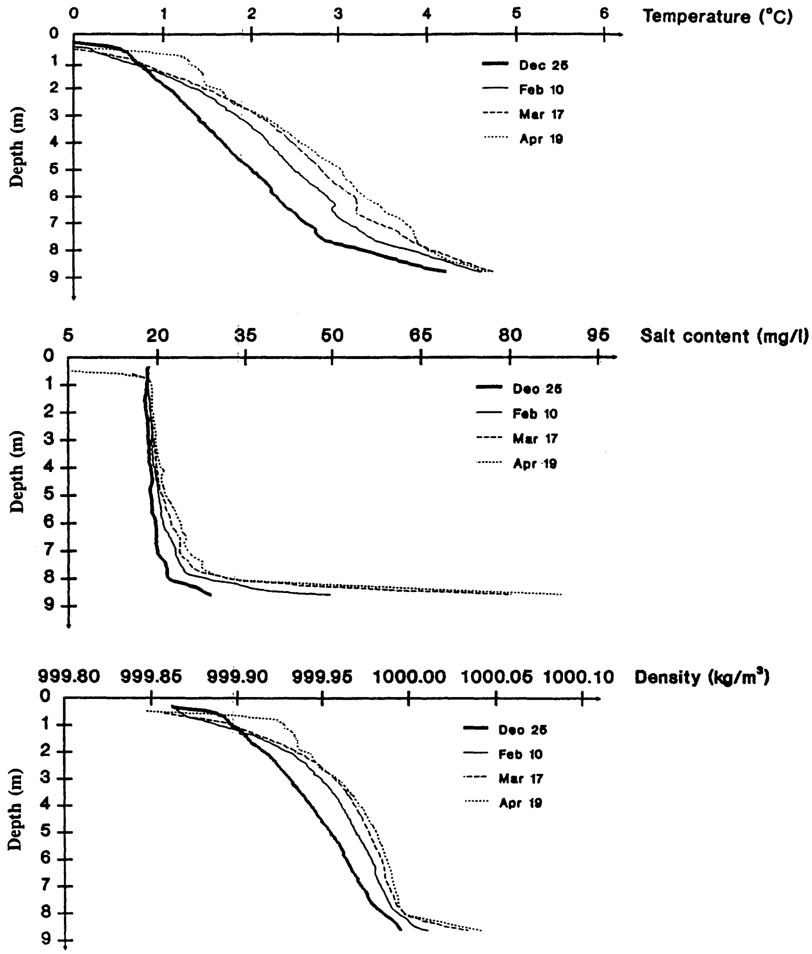


Fig. 7. Vertical temperature, salt content, and density structure recorded during the four surveys in Lake Rindozero at station 3.

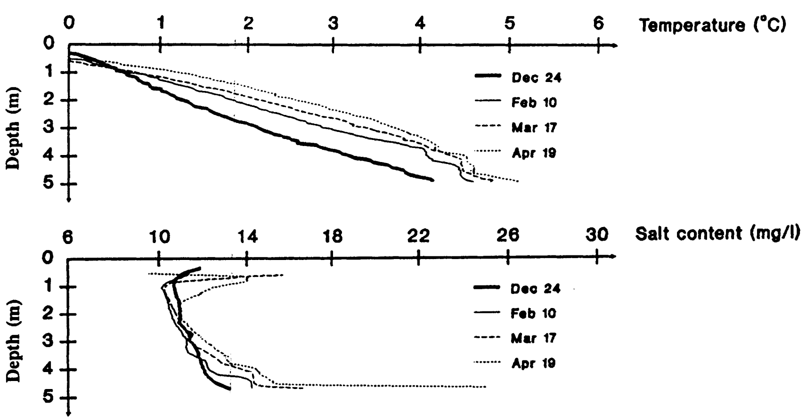


Fig. 8. **cont.**

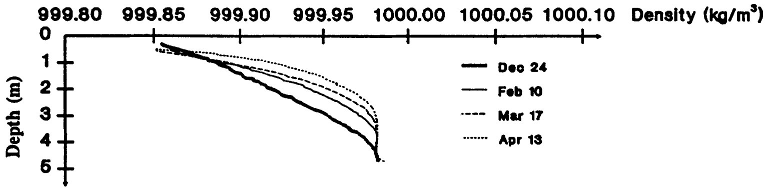


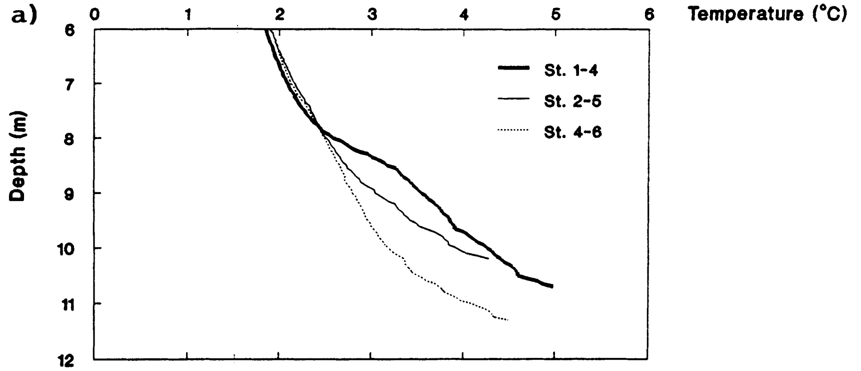
Fig. 8. Vertical temperature, salt content, and density structure recorded during the four surveys in Lake Uros at station 2.

Horizontal Temperature and Salt Content Structures

It is likely that the horizontal temperature differences in an ice-covered lake are small (see, for instance, Bengtsson *et al.* 1996), but this needs to be confirmed, since earlier field investigations have been confined to a few points. To investigate the horizontal temperature and salt content changes between the 49 stations in Lake Vendyurskoe, the mean and standard deviation values were calculated for different depths, see Table 5. The horizontal temperature variation is very small (and random) at most depths during all surveys, with standard deviations about 0.05-0.1°C (relative accuracy in the temperature measurements was 0.003°C). The isotherms can therefore be considered to be horizontal during the main part of the winter. A horizontally homogeneous temperature structure was also indicated in the other two lakes, although the number of stations there were too few for any certain conclusions. At larger depths (8 m and higher), the horizontal variations in temperature are higher. This is due to that the deep parts at different locations in the lake are not interconnected. Therefore, the heating of the bottom layers proceeds independently, leading to different temperature structures. One example of this is shown in Fig. 9a.

Table 5 – Mean temperature (T_{avg}) and standard deviation (T_{std}) at different depths in Lake Vendyurskoe during survey 1, 3, and 4 in winter 1994/1995.

	Survey 1 (December 20-25)			Survey 3 (March 14-19)			Survey 4 (April 13-16)		
Depth (m)	No. of Stations	T_{avg} (°C)	T_{std} (°C)	No. of Stations	T_{avg} (°C)	T_{std} (°C)	No. of Stations	T_{avg} (°C)	T_{std} (°C)
1	49	0.62	0.09	47	0.33	0.05	32	0.41	0.08
2	49	1.00	0.05	47	1.10	0.04	32	1.17	0.05
3	47	1.20	0.07	45	1.60	0.04	30	1.73	0.05
4	41	1.44	0.07	40	2.01	0.05	28	2.19	0.05
5	34	1.67	0.07	33	2.38	0.08	21	2.52	0.07
6	27	1.90	0.06	25	2.71	0.07	17	2.90	0.07
7	23	2.17	0.06	21	3.10	0.08	14	3.30	0.09
8	15	2.50	0.04	13	3.50	0.15	9	3.68	0.18
9	8	3.00	0.26	6	3.97	0.18	4	4.13	0.21
10	5	3.69	0.49	4	4.53	0.28	3	4.68	0.23



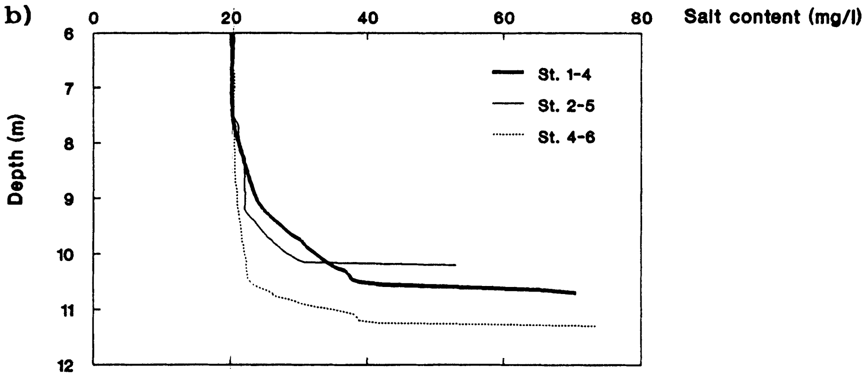


Fig. 9. Temperature (**a**) and salt content (**b**) structure below 6 m depth at three local hollows in Lake Vendyurskoe during the first survey.

Table 6 – Mean salt content (S_{avg}) and standard deviation (S_{std}) at different depths in Lake Vendyurskoe during survey 1, 3, and 4 in winter 1994/1995.

	Survey 1 (December 20-25)			Survey 3 (March 14-19)			Survey 4 (April 13-16)		
Depth (m)	No. of Stations	S_{avg} (mg l^{-1})	S_{std} (mg l^{-1})	No. of Stations	S_{avg} (mg l^{-1})	S_{std} (mg l^{-1})	No. of Stations	S_{avg} (mg l^{-1})	S_{std} (mg l^{-1})
1	49	20.0	0.7	47	19.2	0.9	32	20.4	1.0
2	49	19.6	0.3	47	19.4	0.4	32	19.5	0.6
3	47	19.6	0.3	45	19.7	0.2	30	19.6	0.2
4	39	19.8	0.4	38	19.9	0.3	26	19.8	0.2
5	34	19.9	0.4	31	20.1	0.7	21	20.3	0.7
6	27	20.0	0.4	25	20.2	0.4	17	20.5	0.3
7	21	20.2	0.3	19	20.7	0.4	12	21.1	0.5
8	15	20.6	0.4	13	21.8	0.9	9	22.3	0.6
9	7	21.4	1.2	6	23.9	1.9	4	25.2	1.2
10	4	26.2	5.2	3	30.1	3.4	2	29.5	0.9

As seen in the figure, the temperature at different locations is about the same above 8 m depth, while below this depth it may differ by more than 1°C.

The water temperature is higher further down into the water than near the ice. Thus, the average profile temperature is higher the deeper the water depth is. For instance, during the first survey in Lake Vendyurskoe the average temperature at station 4-1 (bottom depth 3.5 m) was 0.95°C, compared to 1.98°C at station 4-6 (bottom depth 11.3 m). The average temperature in a vertical generally increases during the winter. This increase is larger at stations with bigger bottom depths. For instance, the average temperature increase between the first and fourth survey in Lake Vendyurskoe at station 4-1 was 0.06°C, and 0.77°C at station 4-6, indicating that heat transferred from sediments to water at shallow depths is transported towards the deeper parts of the lake.

There is a weak increase of salt content values in the main part of the water column with depth and time, see Table 6. The salt content shows only very small variations between stations, with standard deviations of the order of 0.5 mg l^{-1}, and can be considered to be horizontally homogeneous. This horizontally homogeneous condition was also indicated in the other two lakes. At large bottom depths (7 m or more), the salt content increases significantly. At water depths where the water masses are separated by shallow sills, there are horizontal variations in salt content, see Fig. 9b, indicating restricted water exchange.

Temperature, Salt Content and Density Profiles in the Vicinity of the Ice

The temperature and salt content structure below the ice-water interface is of especial interest, since heat conducted from water to ice is the main source for heat loss during winter and ice growth or melting causes release of salts or water with low salt content, which in turn affects the density distribution. Therefore, registrations of temperature and conductivity with fine resolution (8 mm) of the vertical positioning of the measurements were made beneath the ice at the stations along cross-section 4 in Lake Vendyurskoe, and at the stations in Lake Rindozero and Lake Uros. Examples of the temperature structure in the vicinity of the ice for one station in each lake are shown in Fig. 10-12. The temperature gradient does not change much in the upper metre, being typically about 1°C m^{-1}, and is almost constant in the upper 10-20 cm during each of the three first surveys in all three lakes. The difference in the gradient magnitude is also quite small between the three first surveys. The heat flux from water to ice can roughly be estimated using the gradient method. With the typical temperature gradient given above and the molecular value of conductivity for water at 0°C of 0.57 W m^{-1} $°C^{-1}$, we get a heat flux from water to ice of 0.6 W m^{-2}. This is close to the value reported by Bengtsson and Svensson (1996) of 1 W m^{-2}, obtained as an average for eight Swedish lakes.

During the fourth survey, solar radiation that penetrated through the ice had warmed the water close to the ice, leading to increased temperature gradients. This is most clear for Lakes Rindozero and Uros. In Lake Uros and at most stations in

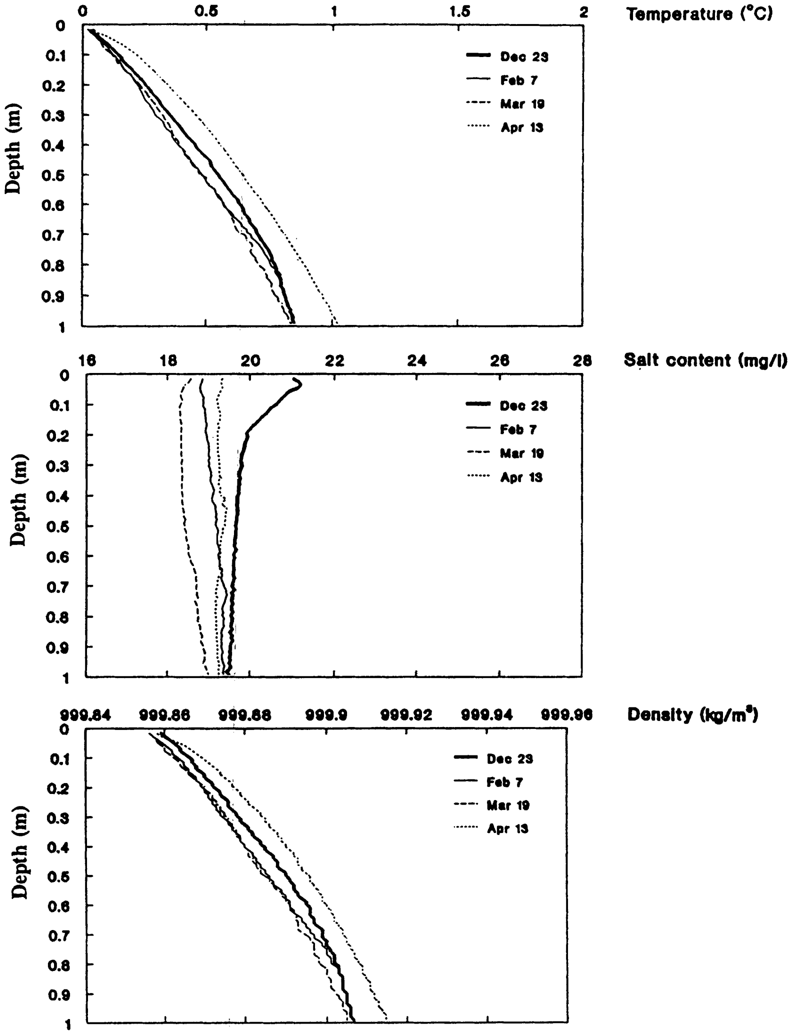


Fig. 10. Vertical temperature, salt content, and density structure in the vicinity of the ice recorded during the four surveys in Lake Vendyurskoe at station 4-6.

Lake Vendyurskoe, the salt concentrations in the vicinity of the ice do not show any major variations between surveys. However, at some stations in Lake Vendyurskoe, higher salt concentrations were observed during the first survey due to salt release from the freezing water during ice growth. These higher salt concentrations below the ice were not pronounced during the other surveys, probably because further ice growth was mainly located in the water saturated snow layer on top of the ice, and due to a slower ice growth rate. At station 1 and 2 (see Fig. 11) in Lake Rindozero and at station 3-3 in Lake Vendyurskoe, the relatively low salt concentrations in the surface layer indicate a local influence by river inflow water.

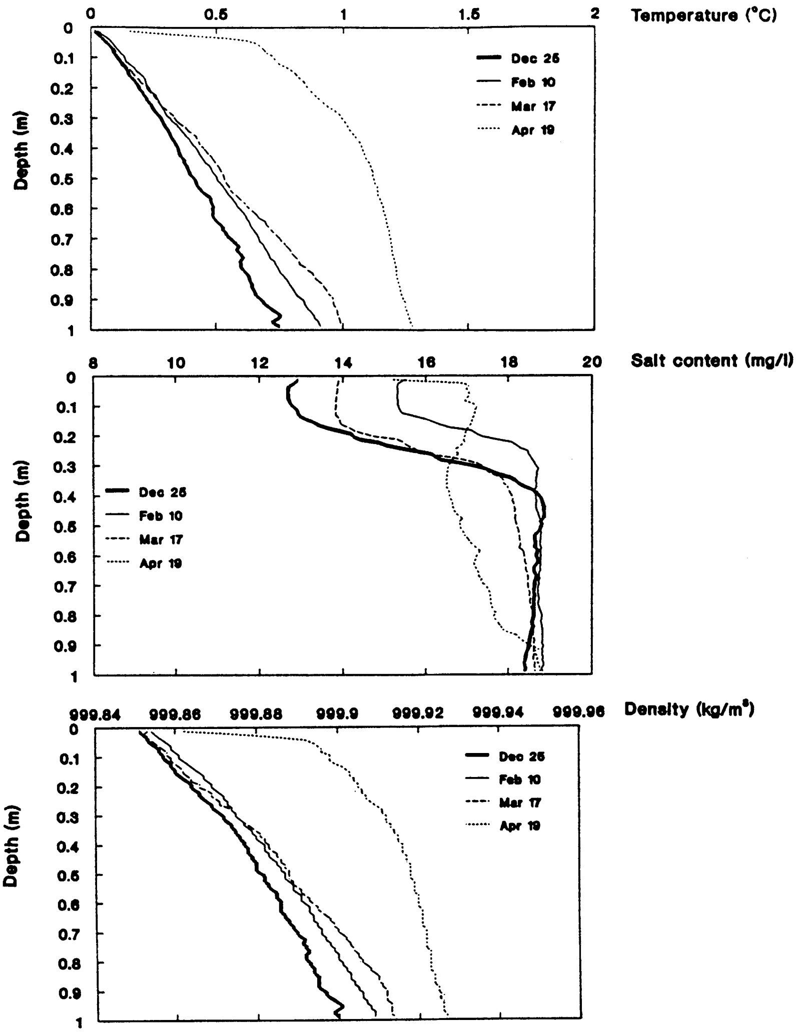


Fig. 11. Vertical temperature, salt content, and density structure in the vicinity of the ice recorded during the four surveys in Lake Rindozero at station 2.

Temperature, Salt Content and Density Profiles at the Sediment Water-Interface

The heat and mass released from bottom sediments are the main sources for heat and mass increases in an ice and snow covered lake without significant in/outflows (Malm *et al.* 1996). The exchange of soluble mineral matter through the water-sediment interface is caused mainly by mineralization of organic matter in the upper layer of the sediments and diffusion of different ions from deeper layers of the sediments (Lozovik 1991).

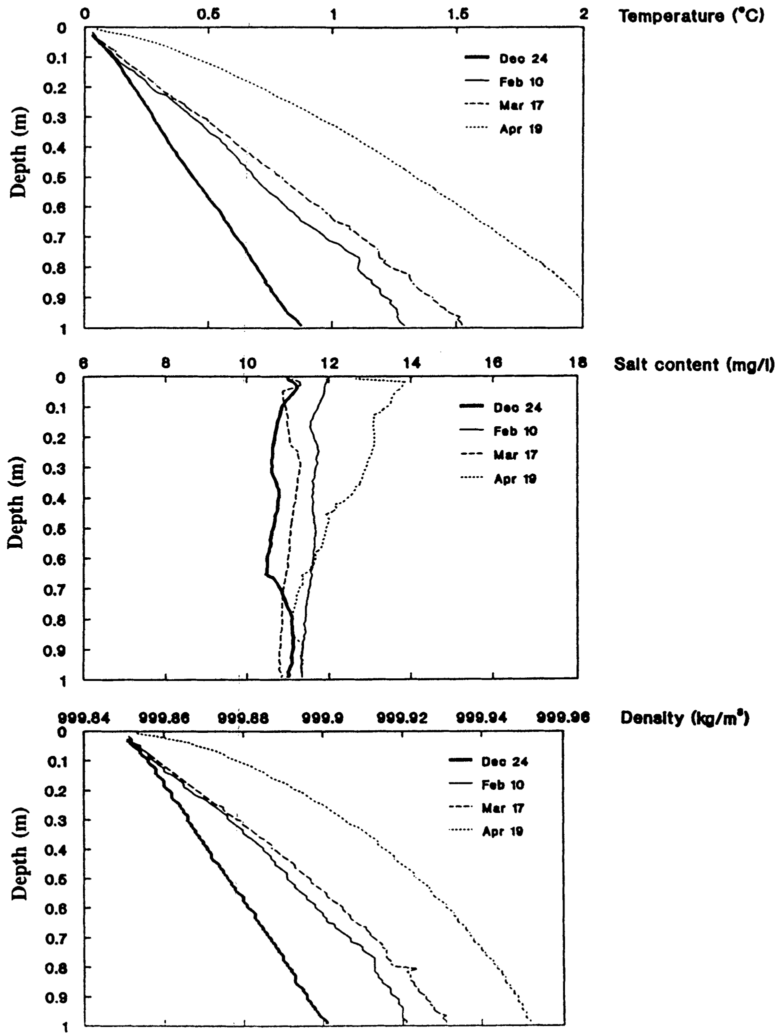


Fig. 12. Vertical temperature, salt content, and density structure in the vicinity of the ice recorded during the four surveys in Lake Uros at station 1.

In order to investigate the sediment heat and mass fluxes and the existence, features, and vertical extent of the bottom boundary layer in an ice-covered lake, measurements of temperature and salt content structure (vertical space resolution equal to 8 mm) were made at the sediment-water interface at stations along cross-sections 4, 5 and 6 in Lake Vendyurskoe during the fourth survey. The border between water and sediments was distinguished by means of an optical sensor.

The measurements showed, that the registered temperature and salt content profiles can be divided into two types, namely "slope" (see, Fig. 13a) and "hollow" (see Fig. 13b) types, referring to the bottom topography. The slope type of profile is lo-

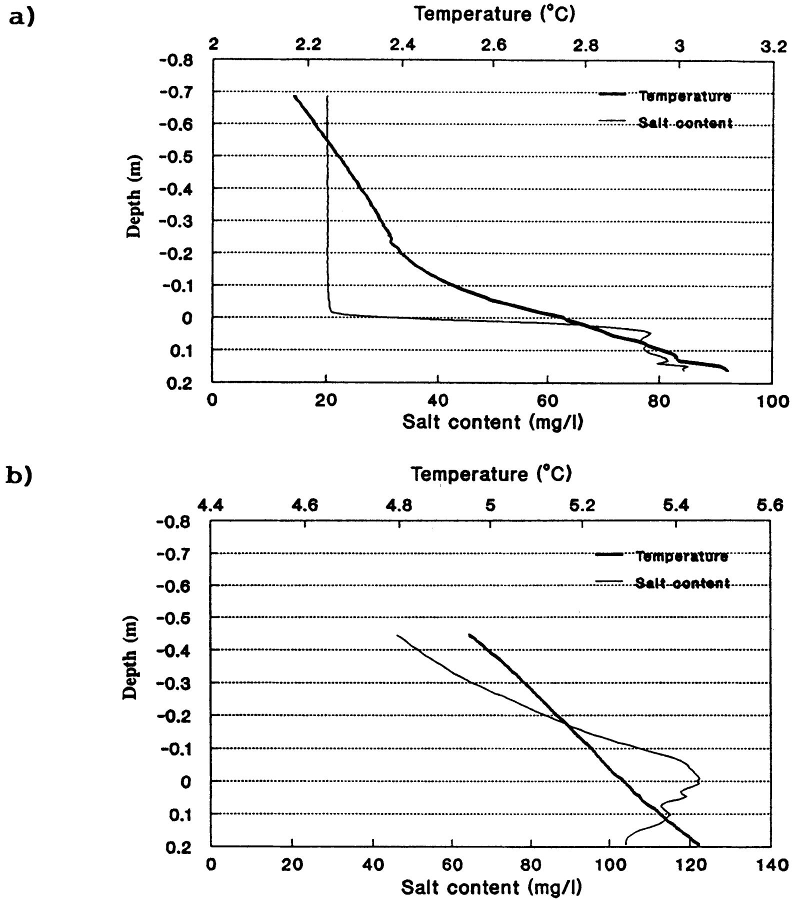


Fig. 13. Temperature and salt content profiles at the sediment-water interface at station 4-6 – **a**, and 6-4 – **b**, on April 16.

cated where the bottom is inclined in comparison to the horizontal plane, and the hollow type of profile is located in the deep parts of the lake or at local hollows. With respect to temperature, the slope type of profile is characterized by a constant temperature gradient in the bottom sediments, which above the interface gradually decreases until it matches the gradient typical for the interior water in the lake at this depth. The vertical extent of the thermal boundary layer with gradual decrease in temperature gradient was of the order of 1 dm for all investigated profiles of slope type. With respect to salt content, the profile of slope type is characterized by a rapid change in salt concentration over the sediment-water interface (gradients up to 10-20 mg l^{-1} cm^{-1}). Just 1-2 cm above the bottom the salt content obtains values typical for the interior water at this depth. Below the interface, the gradients gradually decrease, at some points even being negative. The highest salt concentrations in sediments were observed at stations where the content of organic matter in sediments was high.

The profiles of hollow type, registered at stations in the deep parts of the lake or at local hollows, are characterized by a constant temperature change with depth both below and above the interface, indicating a constant rate of heat conduction in the bottom layer. The salt content profile represents much smaller gradients above the sediment-water interface, compared to the profile of slope type, but a much thicker layer of high salt content, with the maximum value located on the interface itself. Within the sediments, the salt concentration decreases downwards. Although the temperature stratification is unstable in most of the hollow type profiles (the temperature of maximum density for freshwater is ~4°C), the density stratification is not, due to the salt content increase with depth. This situation is typical for all "deep" water regions with temperatures above 4°C in the three lakes.

The observed temperature gradients in the upper 10 cm of the sediments were in the range 1-7 °C m^{-1}, where the higher values were obtained in early winter and at small bottom depths. Assuming that the sediment conductivity is equal to that of water (0.57 W m^{-1} $°C^{-1}$), as the porosity of the upper layer of sediments in general was higher than 95%, the corresponding heat flux from sediments to water is in the range 0.5-4 W m^{-2}. These sediment heat flux values are consistent with those obtained by other investigators (see, for instance, Likens and Ragotzkie 1965; Welch and Bergmann 1985; and Svensson 1986).

Measurement Results – Late Winter

In the middle of April, heating due to solar radiation penetrating through the ice cover became apparent in all three lakes, see Figs. 3-5 above. The temperature increased rapidly, and exceeded 4°C throughout the water column (except in the vicinity of the ice) in the end of April in Lake Uros and in the middle of May in Lake Vendyurskoe and Lake Rindozero. There is a main difference in the development of the vertical temperature structure during this last period before ice break-up between Lake Vendyurskoe and Lake Rindozero compared to Lake Uros. In the first two lakes, the penetrating solar radiation mainly heats the water close to the ice, until this layer becomes hydrostatically unstable and convection begins. The vertical temperature structure is then characterized by a thin boundary layer in the vicinity of the ice, where the temperature increases rapidly with depth, a convectively mixed layer with a depth constant temperature, and the "old" winter temperature structure in the lower part of the water column. The temperature and thickness of the convectively mixed layer increases steadily with time until the temperature of 4°C is exceeded.

In Lake Uros the vertical temperature structure is different. The penetrating solar radiation is distributed more homogeneously over the water column, and the temperature structure is hydrodynamically stable until a temperature of 4°C is exceeded.

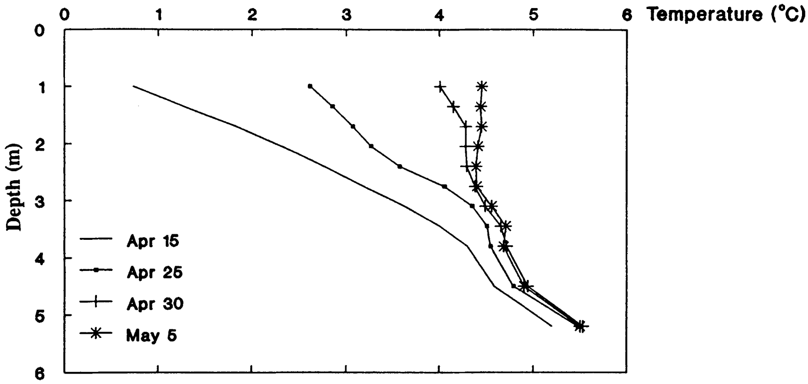


Fig. 14. Temperature development at station 2 in Lake Uros as registered by a thermistor chain during the period April 15 to May 5. The bottom depth is 5.5 m.

Therefore, no under-ice convection in the conventional sense occurs in this lake. However, when the temperature exceeds 4°C in the interior, hydrodynamic instability develops, since heavier and colder water lies above lighter and warmer water. As a result, a homogeneously mixed layer forms in the interior which grows in thickness with time. This is shown in Fig. 14 for Lake Uros. It is likely that this type of interior convection develops in shallow ice-covered lakes, which do not experience under-ice convection.

There are presumably two main reasons for the absence of under-ice convection in Lake Uros: the higher vertical temperature gradient (~1°C m^{-1}) compared to the other two lakes (vertical temperature gradients about 0.5°C m^{-1} in both lakes) before solar heating started, and different water characteristics in the three lakes, where Lake Uros suggestively has a smaller capacity for absorption of solar radiation per unit volume of water. Water samples were collected in each lake and the extinction coefficient was determined as a function of radiation wave length, using a SPECORD UV-VIS. The results are given in Table 7. As seen in the table, the smallest water extinction coefficients are obtained for Lake Uros.

The heat content increases during the spring heating period (April 15 to ice break-up on May 20) in Lakes Vendyurskoe, Rindozero, and Uros are 504, 74, and 194 TJ, respectively. The corresponding average rates of heat content change for a water column in the three lakes are 15.6, 13.2, and 14.5 W m^{-2}, which are one order of magnitude higher than during early and mid-winter. Therefore, solar radiation penetrating through the ice can be expected to be the dominant heat source during this period.

A special study was devoted to the "solar heating" period during the second half of April. Solar radiation (incident, reflected, and the amount penetrating through the ice), temperature, and conductivity profiles were measured during the period April 13-23 at station 4-3 in Lake Vendyurskoe. The daily average of the solar radiation

Table 7 – The extinction coefficient as a function of radiation wave length (visible part) for water samples from the three lakes.

Radiation wave length (μm)	Extinction coefficient (m^{-1})		
	Rindozero	Vendyurskoe	Uros
0.4	14.82	4.69	1.14
0.45	6.75	2.23	0.67
0.5	3.76	1.09	0.45
0.55	1.95	0.80	0.34
0.6	1.41	0.58	0.40
0.65	1.33	0.55	0.50
0.7	1.34	0.74	0.70
0.75	2.99	2.62	2.58

penetrating to the water was about 1 W m^{-2} on April 14, *i.e.* in the same order of magnitude as the sediment heat flux and the heat flux from water to ice, and rapidly increased thereafter reaching ~30 W m^{-2} on April 23. This is mainly due to rapid snow cover melting which disappeared on April 17 at the location of measurements, and a continuous decrease in ice thickness (about 20 cm during the period) and surface albedo. The average solar radiation heat flux to the water during the ten day period was ~10 W m^{-2}. Measurements of temperature and conductivity profiles in the vicinity of the ice at station 4-3 are presented in Fig. 15. The heating due to penetrating solar radiation, before the onset of convection, is limited to the first metres below the ice. When convection began, in late afternoon/evening of April 20, the vertical temperature distribution was characterized by an upper boundary layer with a sharp temperature increase, a convectively mixed layer with constant temperature, and the "old" winter temperature structure below. During the period April 14-23, the ice cover decreased in thickness with about 20 cm. The melt water, having a very small salt content and thus a comparatively smaller density, remained in a layer in the vicinity of the ice. On April 23 this melt water affected layer had increased in thickness to approximately 30 cm. The less saline water in the vicinity of the ice has a pronounced effect on the density distribution. Therefore, a temperature inversion at the top of the mixed layer, although not observed, does not necessarily imply a density inversion.

The registered density profiles, calculated from the temperature and conductivity values, do not show any pronounced inversions at the time of onset of convection. It is therefore of interest to estimate how large this density (temperature) inversion has to be to cause convective mixing. Hydrodynamic instability occurs when the Rayleigh number exceeds a certain critical value ($Ra_c \approx 10^2$-10^3, see Turner 1973; Matthews and Heaney 1987),

$$\frac{g\,b}{\nu\,\kappa}\,\delta T \lambda^3 > Ra_c \qquad (2)$$

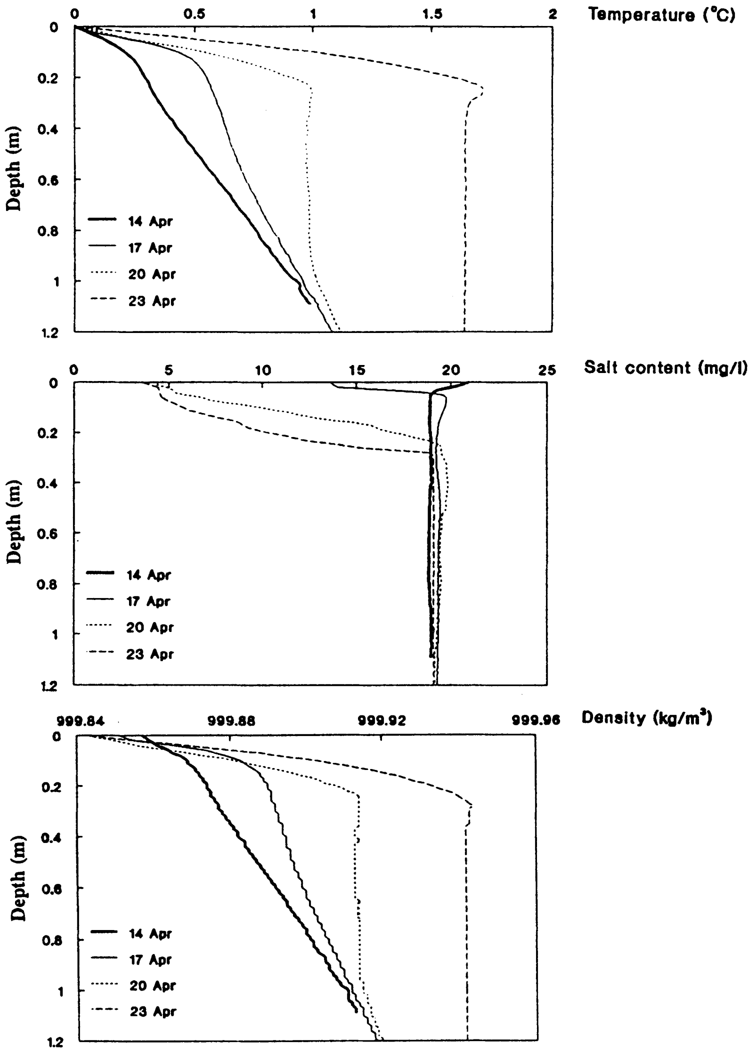


Fig. 15. Vertical temperature, salt content, and density structure in the vicinity of the ice recorded during April 14-23 at station 4-3 in Lake Vendyurskoe. All registrations occurred during evening time (between 6 and 7 pm).

Here, λ is a length scale corresponding to the distance over which the density profile is hydrodynamically unstable, δT is a temperature difference associated with the inversion, g is gravitational acceleration, b is the thermal expansion coefficient, ν is kinematic viscosity, and κ is molecular thermal diffusivity. The value of λ depends on the extinction coefficient and can comprise from fractions of a metre up to several metres. In our case, λ was defined as the thickness of the layer that has an approx*imately neutral stratification* just before onset of convection, being ~0.7 m (estimat-

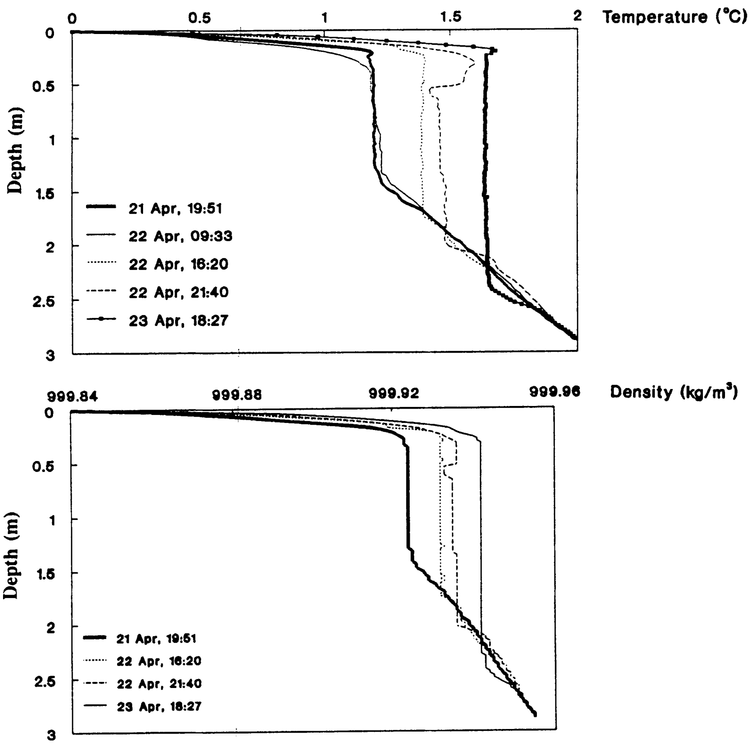


Fig. 16. Vertical temperature and density structure recorded during April 21-23 at station 4-3 in Lake Vendyurskoe.

ed from the registered temperature data in the vicinity of the ice during the afternoon on April 20). This results in an extremely small value on the temperature difference ($\delta T \sim 10^{-4}$-10^{-6} °C), and explains the absence of detectable temperature inversions at the time of onset of convection. It is also in good agreement with the results of Petrov and Soutyrin (1985), who found that very small temperature differences (10^{-4}-10^{-7} °C) can initiate convective motions.

The growth of the convectively mixed layer during the period April 21-23 is illustrated in Fig. 16. The temperature gradients within the surface boundary layer increased continuously as well as the vertical extent of the mixed layer, being ~2 m in the evening of April 23. The effects of penetrative convection, *i.e.*, the erosion of the stably stratified temperature structure by convective motions, are visualized on April 22 by the formation of a transition layer between the mixed layer and the stably stratified water beneath at a depth of ~2 m. In the evening of April 23, the thickness of and the temperature jump within this transition layer were 2 dm and 0.2°C, respectively.

The entrainment efficiency, *i.e.*, the increase in rate of mixed layer deepening due to penetrative convection, can be estimated for April 22 using the following expres-

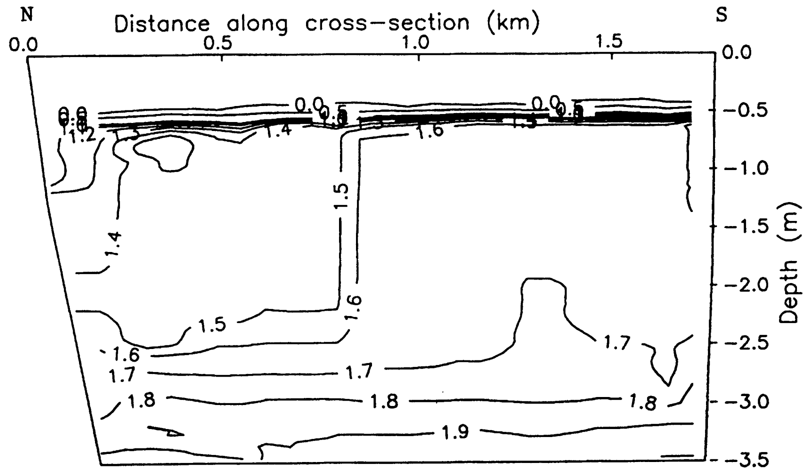


Fig. 17. Temperature distribution in the upper 3.5 m layer along cross-section 4 in Lake Vendyurskoe during the evening of April 22. The isotherm spacing is 0.5°C between 0°C and 1°C, and 0.1°C between 1°C and 2°C. Left-hand side of the figure corresponds to the northern part of the section, and the right-hand side the southern part.

sion proposed by Petrov and Soutyrin (1985)

$$\varepsilon = \frac{\Delta h}{\Delta h_*} \quad (3)$$

Here Δh stands for the measured value of the increase in convectively mixed layer (CML) thickness during a day; $\Delta h_* = [(h_0^2+2Q_d/\rho c_p\gamma)^{1/2}-h_0]$ stands for the daily increase in CML thickness, not accounting for penetrative convection; Q_d is daily average income of heat taken up by the water; h_0 is initial thickness of CML before solar heating started; ρ is water density; c_p is volumetric heat capacity of water; and γ is the temperature gradient in the upper part of the stably stratified layer. With following observed values on April 22, $\Delta h = 0.7$ m, $Q_d = 1.7\times10^6$ J m^{-2}, $h_0 = 1.3$ m, $\rho c_p = 4.2\times10^6$ J m^{-3} °C^{-1}, and $\gamma = 0.5$°C m^{-1}, we get an entrainment efficiency, $\epsilon = 1.3$, that is, the rate of mixed layer deepening is ~30% higher compared to the case when penetrative convection is ignored. This illustrates the importance of accounting for penetrative convection for estimations of mixed layer deepening rates.

It is likely that there were spatial variations in the amount of solar radiation penetrating through the ice during the spring heating period, as differences in both ice and snow cover thickness, as well as in snow and ice structure were observed at the measurement stations. As a consequence, it seems probable that the temperature structure during the convective period may show horizontal differences. To investigate this, a temperature survey was performed along cross-section 4 in Lake Vendyurskoe in the evening (between 7:30 and 10:30 pm) of April 22 (the time of measurements was chosen so that the influence of solar heating on the obtained "instantaneous" temperature distribution would be small). The registered temperature distribution is given in Fig. 17. There is no pronounced local variations in the vertical temperature distribution between stations. Instead, the vertical temperature structure is different between the two halves of the cross-section, with a horizontal temperature jump of 0.2°C in between. The vertical extent of the mixed layer is greater on the southern side (~2 m) than on the northern side (~1.5 m) of the cross-section. Also the temperatures within the convectively mixed layer are higher on the southern side (~1.6-1.7°C) than on the northern side (~1.4-1.5°C) of the cross-section.

Conclusions

During the whole ice-covered period, the heat content in the three investigated lakes increased. A weak stable stratification existed in the lakes at ice formation, with average temperatures about 1°C. Thereafter, the stability of the stratification gradually increased, mainly due to pronounced temperature increases in the bottom layers. In mid-winter the bottom layer in the deep parts of the lake obtained temperatures above 4°C. The density stratification in these layers was stable, however, due to higher salt contents in the vicinity of the bottom. Generally, the temperature distribution was characterized by horizontal isotherms.

From the middle of April until ice break-up, heating due to penetrating solar radiation dominated the development of the thermal regime. Typical daily heat flux averages in the second half of April were about 10-30 W m^{-2}.

A layer of melt water, with low salt content, was observed in the vicinity of the ice from mid-April and onwards. This layer partially counteracted negative temperature gradients, and thus had a certain influence on the hydrostatic stability.

Under-ice convection developed in two (Rindozero and Vendyurskoe) of the three investigated lakes during the second half of April, when heating due to penetrating solar radiation became apparent. Although no under-ice convection in the conventional sense occurred in the third lake (Uros), interior convection developed when the temperature exceeded 4°C (the temperature of maximum density) there. The absence of under-ice convection in Lake Uros is most likely due to the higher vertical temperature gradient in the lake before spring heating and smaller extinction coefficient than in the other two lakes.

The temperature differences associated with the onset of convection in the investigated lakes are small (estimated to less than 10^{-3} °C). The effects of penetrative convection were visualized by formation of a transition layer between the mixed layer and the stably stratified water beneath. The thickness of and the temperature jump within this transition layer were 2 dm and 0.2°C, respectively, after two days of convective mixing. Horizontal temperature differences of 0.2-0.3°C were observed during the period of convection, most likely caused by spatial differences in ice thickness and surface albedo.

Acknowledgements

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Address:
Joakim Malm, Arkady Terzhevik, Lars Bengtsson,
Department of Water Resoruces Engineering,
Lund University,
P.O. Box 118,
S-221 00 Lund,
Sweden.

Pjotr Boyarinov, Alexander Glinsky,
Nikolaj Palshin, Michail Petrov,
Northern Water Problems Research Institute,
Karelian Scientific Center,
Russian Academy of Sciences,
185 003 Petrozavodsk, Urickogo 50,
Russia.