Aquat Ecol (2009) 43:629–639
DOI 10.1007/s10452-009-9277-0

Spatial and temporal variations of the water–sediment thermal structure in shallow ice-covered Lake Vendyurskoe (Northwestern Russia)

G. E. Zdorovennova

Received: 11 June 2009 / Accepted: 22 July 2009 / Published online: 11 August 2009

Abstract The thermal structures in the vicinity of the ice–water and water–sediment boundaries of a shallow lake, L. Vendyurskoe (Northwestern Russia) during four winter seasons are described. The heat flux at the water-ice boundary was 0.1–0.2 W m^{-2} during winter. The maximal heat flux at the water–sediment boundary was 4.5 W m^{-2} at the beginning and 0.5 W m^{-2} at the end of winter. The daily average value of the solar radiation penetrating into the water was 0.5 W m^{-2} during main part of winter and 2–50 W m^{-2} during April. During winter, temperature showed an oscillation in the vicinity of the sediment-water interface. Most periods corresponding to the main oscillation frequencies in the near-bottom water layer (0–0.4 m) and upper layer sediment (0–0.35 m), identified by FFT analysis, fall within the scale of synoptic variations (3–10 days), and in a number of cases were equal to 1 day. The theoretical periods of the first baroclinic seiche mode of Lake Vendyurskoe are 4.5–8.5 days that compares well with identified temperature oscillation periods. The comparison between the rate of heat content change in a water column and the difference of vertical heat fluxes from sediment to water and from water to ice show that the horizontal heat transport takes place in the lake during winter as a result of heat advection along the bottom.

Keywords Ice · Lakes · Sediment · Thermal structure

G. E. Zdorovennova (✉)
Northern Water Problems Institute, Karelian Scientific Centre, Russ. Acad. Sci., Aleksander Nevsky st. 50, 185030 Petrozavodsk, Russia
e-mail: grma2007@rambler.ru

Introduction

The thermal structure of lake sediments in shallow dimictic lakes is characterized by the year-to-year, seasonal and synoptic variability. The lake sediments accumulate heat during spring and summer warming and release this stored heat during autumn and winter cooling. Lakes are ice-covered for several months of the year in the temperate zone. Average temperature of ice formation of lake water mass is 0.5–1.0°C (Bengtsson et al. 1996). After the ice formation in surface layers, temperature increases in the near-bottom water layers due to the heat release from bottom sediments. Estimates of values of the heat flux from bottom sediments to water during winter are in the range 0.5–4.5 W m^{-2} (Bengtsson and Svensson 1996; Malm et al. 1997b). When there are no other heat sources (heat exchange with atmosphere, river inflow, solar radiation penetrating through the ice), the heat flux from bottom sediments plays an important role for the exchange of the heat content of small shallow lake during winter. The vertical temperature profile has a continuous increase from 0°C at the ice–water interface to 2–4°C near bottom in the end of winter, generally the temperature rise is limited to 4–5°C (Birge et al. 1927; Bengtsson 1996; Ryanzhin 1997). The lake sediments accumulate heat during summer more intensive near the shores than in deeper parts of a lake. In early winter heat fluxes from bottom sediments to water are greater near the shores (Malm et al. 1997a). Horizontal irregularity of heat flux from bottom sediments is determined by difference of temperature in the near-bottom water layers. The transport of warmer, heavier water (freshwater has its maximum density at 3.98°C) along the bottom layers from shallow to deeper parts of a lake generates the slow bottom current toward deeper parts. The velocities estimated appear to be 0.1 mm s^{-1} (Bengtsson 1996; Malm 1998; Malm et al. 1998). The thermal regime of the water–sediment system plays an important role for the water quality, which in many ways is determined by the saturation of dissolved oxygen. The rate of dissolved oxygen consumption in bottom sediment increases with increase in temperature and flow velocity (Boylen and Brock 1973; James 1974; Mackenthun and Stefan 1998). A decrease in dissolved oxygen concentration leads to the appearance of anaerobic zones in the near-bottom layers of ice-covered lakes and decomposition in lakes ecosystem. The relationship between fluctuations in the heat content of a water column, CO_2 and O_2 concentrations, and the existence of a baroclinic seiche under lake ice has been confirmed by time variations of water temperature and dissolved gas concentrations in ice-covered Lake Placid (USA) (Baehr and DeGrandpre 2002) and by heat content change in L. Vendyurskoe (Petrov et al. 2006). The formation of seiches appears to be due to the vertical fluctuations of ice cover under wind impact (Petrov et al. 2007). Recently the models reproducing the main features of the thermal structure in the ice-water-bottom sediment system (Sahlberg 1988; Ryanzhin 1997; Golosov and Ignatieva 1999), water exchange across the sediment-water interface and dissolved oxygen dynamics in lake during the ice-covered period (Stefanovic and Stefan 2002; Golosov et al. 2007) have been developed. In order to meet the needs of such models, a detailed knowledge on evolution of the thermal structure during winter is required.

The main aim of the project is to determine contribution of horizontal heat transport to the exchange of heat content of water column in shallow-water and deeper parts of a lake. For this, we (1) analyzed spatial and temporal variations of the thermal structure in upper bottom sediment layers and in water; (2) studied spatial and temporal variations of the heat fluxes from sediments to water and from water to ice; and (3) estimated the horizontal heat transport in the lake during the ice-covered period by calculating the changes of heat content in a water column of unit areas. The hypotheses that we tested are: (1) horizontal heat transport in shallow ice-covered lake during winter can exist due to depth distribution and inequality of summer warming and winter cooling of the sediments in shallow-water and deep-water parts of a lake; and (2) horizontal heat transport is the cause of the rapid increase of water temperature in deeper parts of a lake in early winter. Spatial and temporal changes of the water-bottom thermal structure and estimates of heat fluxes from sediment to water and from water to ice are discussed on the basis of data from the thermistor chains deployed during four winters in shallow Lake Vendyurskoe (Northwestern Russia).

Materials and methods

Research site

During four winter seasons, temperature measurements in water and upper bottom sediment layers were performed in a small mesotrophic and shallow (Fig. 1) Lake Vendyurskoe (maximum and mean depths of 13.4 and 5.3 m, respectively, surface area of 10.4 km^2, and volume of $55 \cdot 10^6$ m^3), located in the southern part of Karelia, northwestern Russia (latitude 62°10′–62°20′N, longitude 33°10′–33°20′E). The lake and its catchment area (82.8 km^2) had glacial origin.

The lake has several small inflows and one outflow. The bottom sediment consists of sand in the shallow parts (up to 2–3 m depth), and of silt containing organic mud (thickness of 0.4–1.0 m) in the deeper parts of the lake (Litinskaya and Polyakov 1975). The ice cover on the lake forms in the first half of November; however, in some years this takes place even in December. The lake commonly clears of ice from May 1 to 20. The average duration of the ice-covered period is 5–6 months with the maximum ice thickness of 0.45–0.65 m in April (Petrov et al. 2006).

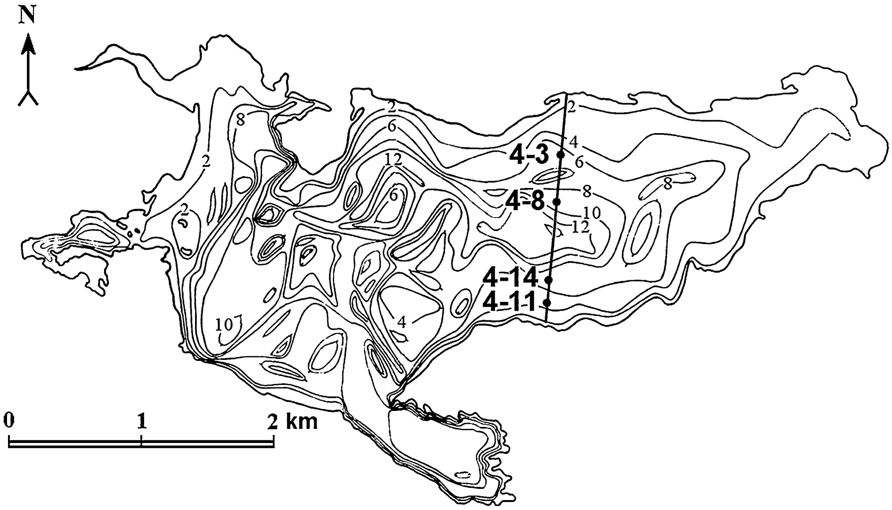

Fig. 1 Bathymetric map and location of measurement stations in Lake Vendyurskoe during winters 1995–1996 (st. 4-11), 1996–1997 (st. 4-8), 2001–2002 (st. 4-14) and 2002–2003 (st. 4-3)

Experimental set-up and methods

Vertical temperature distributions in water and the upper bottom sediment layer were continuously measured with the thermistor chain constructed in Northern Water Problems Institute (thermistor LM-35, accuracy ± 0.15, resolution 0.02°C) deployed during winters 1995–1996, 1996–1997, 2001–2002 and 2002–2003 at different depths (Fig. 1). The sensors were placed at 0.1–1.0 m intervals in water and 0.1–0.3 m intervals in sediments (Table 1). Temperature registrations were conducted each second hour during measurement periods. Information about measurement devices used during the field study is given by Bengtsson et al. (1996) and Malm et al. (1997a). Weather information was obtained from the weather station of Suojarvi located about 70 km from Lake Vendyurskoe.

If the temperature gradient at the sediment-water and water–ice interfaces and the conductivity, λ, are known, the conductive heat fluxes from sediments to water, Q_{bw}, and from water to ice, Q_{wi}, may be estimated from the gradient method:

$$Q_{sw} = Q_{wi} = -\lambda \frac{\partial T}{\partial z}$$

where T is temperature; z is vertical coordinate.

The average temperature gradient was defined to assume that the gradient method could be used with the molecular value of conductivity for water at 0°C, $\lambda = 0.569$ W m^{-1}°C^{-1}, when estimating the heat flux from water to ice and value of conductivity for silt, $\lambda = 0.62$ W m^{-1}°C^{-1}, when estimating the heat flux from sediments to water (Malm et al. 1997a).

The horizontal heat transport in the lake during the ice-covered period was estimated by calculating the changes of heat content in a water column of unit areas:

$$\frac{\Delta \mathrm{HC}}{\Delta t} = Q_{sw} - Q_{wi} + \text{horizontal net heat transport},$$

where

$$\mathrm{HC} = \int_0^H \rho_w c_w T(z,t) \mathrm{d}z.$$

HC is the heat content of a water column with unit area and depth equal to H, and Δt is the time interval (Malm et al. 1997a).

If there is no horizontal heat transport, then the rate of heat content change in a water column should be equal to the heat flux from sediment minus the heat flux from water to ice. Rates of heat content change in a water column and differences of vertical heat fluxes were calculated for station 4-11 (depth 4.38 m) and 4-8 (9.30 m).

The period of a baroclinic seiche can be evaluated using the formula of Gill (1982):

$$T_1 = \frac{2\pi L}{NH} \tag{1}$$

where 1 is a number of the baroclinic seiche mode; L is maximum length of the lake basin, m; H is mean depth of the lake minus the ice thickness, m; N is buoyancy frequency:

Table 1 Temperature differences ΔT (°C) between the beginning and the end of measurement periods

	Period of measurements		
	01 Dec 1995–08 Apr 1996 (winter)	08 Apr 1996–15 May 1996 (spring convection)	15–23 May 1996 (open water)
Station 4-11, depth 4.38 m			
Water			
0.62	−0.09	3.90	1.41
0.72	0.00	3.80	1.40
1.18	0.08	3.59	1.98
4.32	0.97	1.73	1.45
Sediment			
0.04	0.40	1.13	1.45
0.14	−0.08	1.09	0.95
0.29	−0.41	0.93	0.64
0.49	−0.78	0.73	0.41
0.79	−1.33	0.42	0.27
1.09	−1.81	0.20	0.22
	Period of measurements		
	10 Feb 2002–29 March 2002 (winter)	29 March 2002–24 Apr 2002 (spring convection)	
Station 4-14, depth 5.90 m			
Water			
0.58	0.13	1.52	
0.88	0.16	1.90	
5.49	0.33	0.29	
Sediment			
0.04	−0.02	0.08	
0.34	−0.12	0.02	
0.64	−0.21	−0.02	
	Period of measurements		
	21 Dec 1996–27 Feb 1997 (winter)	27 Feb 1997–24 Apr 1997 (spring convection)	
Station 4-8, depth 9.30 m			
Water			
0.61	−0.29	1.48	
0.91	0.01	1.45	
1.17	0.11	1.34	
9.17	1.31	0.53	
Sediment			
0.00	1.24	0.59	
0.20	0.82	0.26	
0.35	0.52	0.18	
0.45	0.17	0.17	
0.55	−0.09	0.12	

Table 1 continued

	Period of measurements	
	21 Dec 1996–27 Feb 1997 (winter)	27 Feb 1997–24 Apr 1997 (spring convection)
0.65	−0.46	0.03
0.75	−0.75	−0.05

	Period of measurements
	23 Dec 2002–31 March 2003 (winter)
Station 4-3, depth 7.9 m	
Water	
0.60	−0.09
0.80	0.02
6.00	0.82
Sediment	
0.00	−0.09
0.10	−0.25
0.30	−0.46
0.55	−0.66
0.75	−0.82
1.05	−1.01
1.35	−1.11

$$N^2 = \frac{g\mathrm{d}\rho}{\rho\mathrm{d}z} \tag{2}$$

where g is gravity acceleration; ρ is average water density (999.957 kg m^{-3}); dρ/dz is average vertical density gradient. Both ρ and dρ/dz were estimated from water temperature and conductivity profiles.

Results

Winter 1995–1996

In the autumn 1995 the cooling period before ice formation was short, and loss of heat from sediments was smaller than usually. Before the ice formation the average lake water temperature from the bottom to the surface was about 0.5°C. The lake froze on 11 November. At the beginning of the "winter" period (see definitions of the periods in Table 1) on 1 December 1995, near the end of the third week after the ice formation, average ice thickness along cross-section, designated on Fig. 1 as solid line was 20 cm and at the end of "winter" period (8 April 1996) was 72 cm.

During the "winter" period between the beginning of December and early April the temperature of thin under-ice water layer decreased at 0.62 m depth in water from 0.20 to 0.11°C (Fig. 2; Table 1). In the deeper water the temperature gradually increased, most intensely in the near-bottom layer: at 4.32 m depth in water from 1.27 to 2.24°C. Sediments temperature decreased most intensely at 1.09 m depth from 5.40 to 3.59°C. At 0.14 m depth in the sediments, the temperature decrease was slight, i.e., from 3.73 to 2.65°C, and at 0.04 m depth it increased from 2.05 to 2.45°C.

During the "winter" period the heat flux at the water–ice boundary directed from water to ice did not exceed 0.1–0.2 W m^{-2}. At the sediments-water boundary the heat flux was directed from sediments to water with maximum flux of 4.5 W m^{-2}. During "winter" period heat flux from sediments to water progressively decreased to 1.3 W m^{-2}. At the beginning of the "winter" period (on 1 December 1995) average ice thickness along cross-section designated on Fig. 1 as solid line was 20 cm and at the end of "winter" period (on 8 April 1996) was 72 cm. The daily average of the solar radiation penetrating into

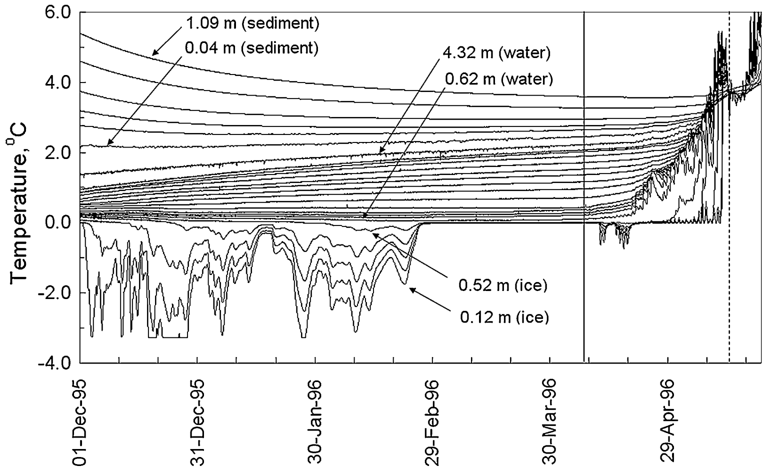

Fig. 2 Temporal changes of temperature in the sediment and water at station 4-11 (depth 4.38 m) between 1 December 1995 and 23 May 1996. *Vertical solid line*—Start of under-ice solar heating (8 April 1996); *Dotted line*—ice-break (15 May 1996) Distance between loggers in ice was 0.1 m, in water 0.38 m, in sediment 0.1–0.3 m

the water was about 0.2 W m^{-2} during March 25–27. Thus, the sediment heat flux during "winter" period was significantly greater than the solar radiation heat flux or heat flux from water to ice.

The "spring convection" period (from 8 April to 15 May 1996) was due to under-ice warming by solar heating. The daily average of the solar radiation penetrating into the water was 6 W m^{-2} on 18 April and then increased to 50 W m^{-2} on 25 April. A diurnal variability of the water temperature and the heat flux at the water–ice boundary were observed. The homogeneous convective layer was formed under the ice cover, with its temperature and thickness increasing every day. During "spring convection" period the water temperature at 0.72 m depth in water rapidly increased and reached 5.45°C before the ice break. The water temperature at 4.32 m depth in water increased from 2.24 to 3.97°C. The sediments temperature also increased and most intensely in the upper bottom layers: at 0.04 m depth from 2.25 to 3.38°C, and insignificantly at 1.09 m depth from 3.59 to 3.79°C. When convection reached the bottom on 8 May 1996 the direction of heat flux was reversed, i.e., from sediments to water to the other way round. At the water–sediment boundary its value was about 1 W m^{-2}. Changes in direction of heat flux at 0.14, 0.29 and 0.49 m depths in sediments happened on 9, 10, 14 May, respectively. Thus, the warming of the bottom sediments in the shallow parts of lake began when it is still ice-covered.

The ice-break occurred on 15 May. After the ice-break, lake was in homothermy due to the total mixing. The average water temperature over the whole lake decreased from 4.3 to 3.5°C during 15–17 May. The temperature of the upper layers of the sediments also decreased after the ice-break during 15–17 May: at 0.04 m depth in sediments from 3.88 to 3.56°C, at 0.14 m depth from 3.75 to 3.63°C, even at 0.29 m depth from 3.65 to 3.63°C. After that during 17–23 May temperature of the water and the sediment increased due to solar heating and wind mixing: at the all depth in water from 3.5 to 5.5°C, at 0.04 m depth in sediments from 3.56 to 5.04°C, at 1.10 m depth in sediments from 3.85 to 4.00°C. During 15–23 May, the diurnal variability of the temperature and heat flux were registered in the sediments at 0.04–0.49 m layer. A week after the ice-break, the direction of the heat flux changed diurnally. The daily maximum heat flux of 2–5 W m^{-2} from the water to the sediments was observed between 1300 and 1600 hours (local time) while at night (2:00 and 6:00 a.m.) there was a maximum flux of 2 W m^{-2} from the sediments to the water.

Winter 1996–1997

Warm weather conditions in the autumn 1996 caused a long cooling period before ice formation. Water and bottom sediments of the lake lost considerable part of heat accumulated during spring and summer. Before the ice formation the average water temperature from the bottom to the surface was about 0.6°C. The lake froze on 12 December. At the start of the measurements period on 21 December 1996, average ice thickness along cross-section, designated on Fig. 1 as solid line was 23 cm and at the end of measurements period (24 April 1996) was 60 cm. The daily average of the solar radiation penetrating into the water was about 2 W m^{-2} on 14 April, increasing to 14 W m^{-2} on 24 April.

The average water temperature before freezing (0.6°C) was similar to that during the preceding year. But the rate of water warming due to heat flux from sediments to water after the ice formation was lower than in the November 1995.

During "winter" period, temperature of the sediment at 0–0.45 m depth increased along with time, but decreased at 0.55–0.75 m depth (Table 1). The heat flux directed upwards from lower layers of sediments to overlying and reached 3.8 W m^{-2} at 0.55–0.75 m depth in sediments in the beginning of the measurement period, decreasing up to 1.3 W m^{-2} at the end. The value of the upwards from sediments heat flux close to the water–sediment boundary was 2.0 W m^{-2} at the beginning and about zero at the end of the observation period.

Winter 2001–2002

The ice thickness was 47 cm at the start of measurements along cross-section (see Fig. 1, solid line) and 54 cm at the end. The daily average of the solar radiation penetrating into the water was about 0.5 W m^{-2} on 10 February, and then it increased from 6 to 25 W m^{-2} during 20–23 April. Spring under-ice warming due to solar heating started after 29 March 2002. During "winter" period the temperature of the sediment decreased in time at 0.04 m depth from 3.6 to 3.58°C and at 0.64 m from 4.35 to 4.14°C. During "spring convection" period direction of the heat flux on the water–sediments boundary was upwards, but when convection reached the bottom, the heat flux changed to downwards. From this moment the temperature of the upper layers of sediments began to increase. In lower layers of sediments still heat flux directed upwards and temperature still decrease. Some time at the some depth in sediments heat fluxes directed upwards and downwards were brought together." During "spring convection" period temperature increased at depth of 0.04–0.34 m and decreased at depth of 0.64 m (Table 1). The maximal heat flux from the sediment to the water reached 3.5 W m^{-2} at the beginning of the "winter" period, and then decreased up to 0.5 W m^{-2} at the end of the measurement period. The heat flux directed from water to ice did not exceed 0.1–0.3 W m^{-2} during the measurement period.

Winter 2002–2003

At the beginning of the measurement period the ice thickness was 29 cm and 68 cm at the end. Solar radiation entering the lake was not measured during December 2002 to March 2003. During the "winter" period the heat flux at the water–ice boundary was directed from water to ice: it did not exceed 0.1–0.4 W m^{-2} but the temperature of thin under-ice water layer decreased (Table 1). In the lower water mass the temperature gradually increased, most intensely at the depth of 6 m. During all three study periods, the temperature of the sediment at depth of 0–1.35 m decreased in time. The maximal heat flux from the sediment to the water reached 2.5 W m^{-2} at the beginning of the "winter" period, and then decreased down to 0.5 W m^{-2} at the end.

Temporal changes of temperature near the water-bottom boundary

After the ice formation a temperature increase occurred in the near bottom layers of a lake due to heat flux from sediments. The thermistor chain data on the temperature structure near the sediment-water interface shows the layer with high temperature gradients of depth from 2 to 4 dm above and 1 to 3 dm below the sediment-water interface. During early, mid- and late winter in this layer, the thermistor chain data revealed oscillations of temperature with amplitude of 0.02–0.25°C (Fig. 3), presumably caused by water motions. Oscillations were registered in all winters covered by temperature measurements near bottom being most pronounced in winters 1995–1996 and 1996–1997.

Most periods (Table 2) corresponding to the main oscillation frequencies of the heat content in the near-bottom water layer (0–0.40 m) and upper layer sediments (0–0.35 m), identified by FFT analysis, fall within the scale of synoptic variations (3–10 days). The periods of temperature fluctuations in the vicinity of the sediment-water interface in a number of cases were equal to 1 day.

The periods of the first baroclinic seiche mode of L. Vendyurskoe calculated from (1) would be 4.5–

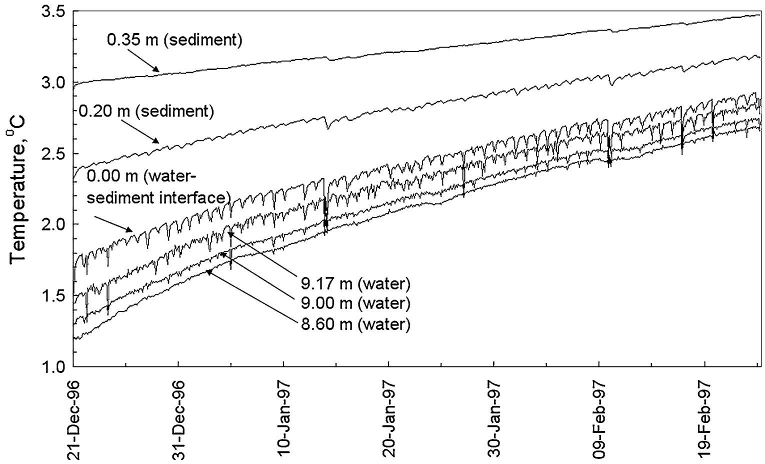

Fig. 3 Development of the temperature in the sediment and in water at station 4-8 (depth 9.3 m) between 22 December 1996 and 24 February 1997

Table 2 Significant ($P < 0.1$) periods oscillation of heat content (T_{HC}) and the first baroclinic seiche mode (T_1) in different water and sediment layers of L. Vendyurskoe

Station, depth	Period of measurements	Layer substance	Layer location m	T_{HC} days	T_1 days
4-11 4.38 m	01 Dec 1995–08 Apr 1996	Water	4.12–4.32	6.3, 1.0	7.7
		Water–silt	4.32–0.04	9.4, 1.0	
		Silt–sand	0.04–0.14	9.4, 7.1, 1.0	
			0.14–0.29	13.9, 9.4	
	09 Apr–14 May 1996	Water	4.12–4.32	4.3, 1.8, 0.8	
		Water–silt	4.32–0.04	2.6, 1.8, 1.5	
		Silt–sand	0.04–0.14	2.6, 1.8, 1.0	
4-8 9.3 m	21 Dec 1996–25 Feb 1997	Water	8.60–9.00	8.2, 1.0	4.5
			9.00–9.17	8.2, 1.0	
			9.17–9.30	8.2, 1.0, 0.5	
		Silt	9.30–0.20	8.3, 6.7, 1.0, 0.5	
		Silt	0.20–0.35	8.4, 6.8, 1.0	
	26 Feb–27 March 1997	Water	8.60–9.00	3.7, 1.0, 0.3	5.1
			9.00–9.17	3.6, 1.0, 0.3	
			9.17–9.30	1.0, 0.3	
		Silt	9.30–0.20	1.0, 0.3	
		Silt	0.20–0.35	3.6, 1.0	
	27 March–24 Apr 1997	Water	8.60–9.00	4.0, 1.0, 0.5	6.0
			9.00–9.17	5.6, 4.0, 1.0, 0.5	
			9.17–9.30	5.6, 4.0, 1.0, 0.5	
		Silt	9.30–0.20	5.6, 1.0, 0.5	
		Silt	0.20–0.35	6.3, 1.0	
4-14 5.9 m	11 Feb–24 Apr 2002	Water	5.41–5.49	6.8, 3.4, 2.4, 1.0	8.5
		Water–silt	5.49–0.04	7.2, 4.7, 3.2	
		Silt	0.04–0.34	7.3	
4-3 7.9 m	25 Dec 2002–31 March 2003	Water	6.00–0.00	7.5, 5.7, 3.0	8.1
		Silt	0.00–0.10	6.7, 5.8, 3.6	

8.5 days that compares well with those of heat content changes (Table 2). The results are in good agreement with those of Petrov et al. (2006) who found the periods of the first baroclinic seiche mode in L. Vendyurskoe for early, mid- and late winter in different years to be 3.5–11.2 days. Baroclinic seiches seem to contribute largely to the time variations in the heat content of a water column (Table 2).

Discussion

As periods of heat content variations are in good agreement with the periods of the baroclinic seiche we suggest that a relationship can exist between the development of baroclinic seiche and temporal variations of thermal structure in shallow ice-covered lake. It is possible that the formation of seiches appears to be due to the vertical fluctuations of ice cover under wind impact (Bengtsson 1996; Petrov et al. 2007) and by air pressure variations over the lake (Malm et al. 1997a, 1998). Probably, the currents in ice-covered lakes without river in- and outflows are generated by horizontal temperature (pressure) gradients (Malm et al. 1996, 1997a). Unfortunately, we do not have available information about variations of wind and air pressure differences over the lake during measurement period.

In any event, the existence of a baroclinic seiche under ice in L. Vendyurskoe did not explain the temperature variations in the vicinity of the sediment-water interface with periods of 1 day. So far we do not know any specific cause for this phenomenon, but it is obvious that near the water-bottom boundary oscillating water motions occur during winter, which can cause mixing and heat and mass transfer from the sediment. The temperature oscillations in the upper several centimeters of the sediment in Lake Müggelsee, Germany, during the winter of 2005/2006 produced vertical density instability and pore-water convection in the upper sediments were associated with a basin-scale internal waves (Kirillin et al. 2009). Two frequency peaks in the oscillations corresponded to two rotational waves, one of Kelvin-wave type and another of Poincaré type wave (Kirillin et al. 2009). Most likely the temperature oscillations in the vicinity of the sediment-water interface in L. Vendyurskoe with period of 1 day during winter are caused by the internal wave of Poincaré type. Therefore, the aim of the future investigation should be to define whether the cause of temperature oscillations in the upper sediments and in water near the bottom is the internal wave of Poincaré type or not.

Horizontal heat transport during winter

In early winter, the maximum of temperature increase occurred in the bottom layers of the deep parts of the lake but maximal heat flux from sediments to water was observed in shallow parts of a lake. This indicates that the heat released from the sediments is mainly transported along bottom slope from shallow to deeper parts. Thereafter, the heat is advected and diffused upwards. This mechanism can explain the temperature increase in the midparts of the water column. Such a mechanism of temperature redistribution from shallow to deeper parts of the lake has been suggested by (Mortimer and Mackereth 1958; Likens and Ragotzkie 1965, 1966; Welch and Bergmann 1985; Rahm 1985).

Rates of heat content change in a water column and differences of vertical heat fluxes were calculated for station 4-11 (depth 4.38 m) and 4-8 (9.30 m). The average rate of heat content change was higher than the average difference of vertical heat fluxes in the deep parts of the lake (Fig. 4b), and lower—in the shallow regions (Fig. 4a) during winter before the under-ice convection period. This allows to assume that in shallow L. Vendyurskoe heat was transported from the shallow regions to deep parts of the lake.

The estimates of heat fluxes from sediments to water, from water to ice and estimates of horizontal heat transport in shallow ice-covered lake during winter are in a good agreement with previous studies (Malm et al. 1997a, b). But our sediment thermistor chain data with high resolution in time (2 h) and in depth of sediments (10–30 cm) are the first used for study of thermal regime of L. Vendyurskoe. Heat fluxes from sediments to water and from water to ice values estimated for all winter season as opposed to previous estimates based on accidental measurements of vertical temperature profiles in early, mid- and late winter. The horizontal heat flux values in the deep parts of the lake are of the same order of magnitude as the sediments heat flux during early and mid winter before solar radiation starts to penetrate through ice

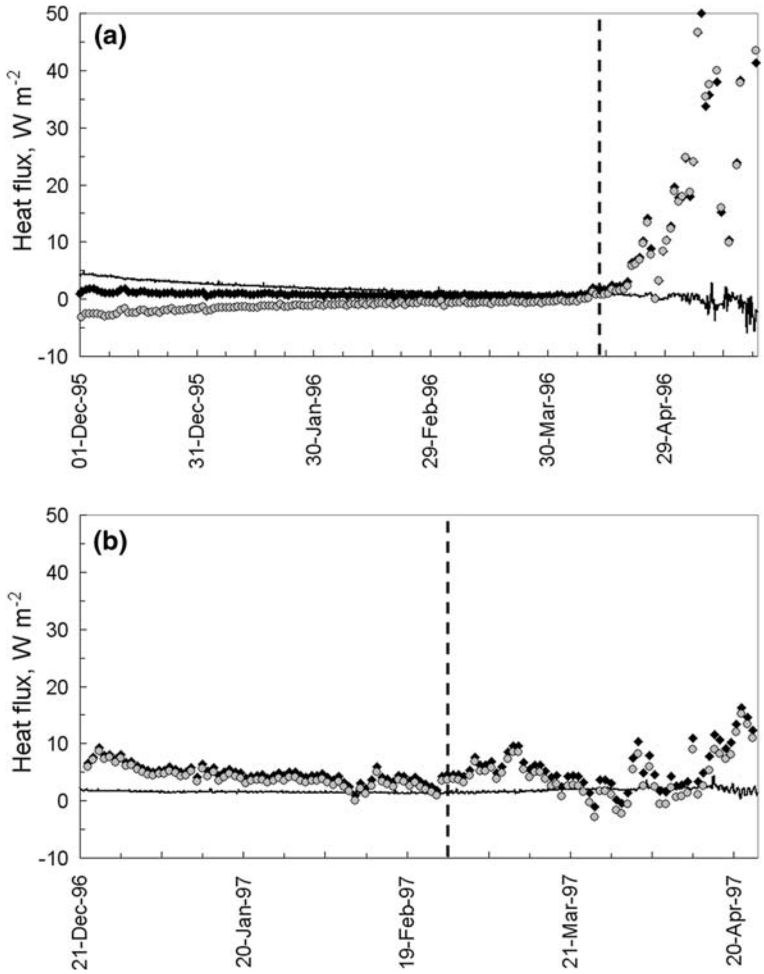

Fig. 4 Change in the heat content of the water column (*black diamond*), heat flux out of sediment minus heat flux from water to ice (*solid line*), and net horizontal heat transport to a water column of unit area (*gray circles*) for: **a**—st. 4-11 (depth 4.38 m) between 1 December 1995–15 May 1996, **b**—st. 4-8 (depth 9.30 m) during 22 December, 1996–20 April 1997. *Vertical dotted line*—Start of spring under-ice solar heating

cover. Therefore, it is necessary to take the horizontal heat transport into consideration in predicting the thermal regime of shallow lake in early and mid winter.

Conclusions

Thermistor chains data demonstrated a similar development of the thermal structure in the upper bottom sediment layer during four winter seasons. The temperature of the upper (0.1–0.5 m) sediment continuously increases during winter due to heat released from deeper layers. However, once the spring convection mixing reaches the bottom, the temperature of the underlying layer starts to increase already when the lake is still covered with ice.

The data analysis suggests that the oscillation of temperature in the vicinity of the sediment-water interface with synoptic periods (3–10 days) is probably seiche-induced due to the vertical fluctuations of the ice cover under wind impact or by air pressure variations over the lake. However, baroclinic seiche does not explain the 1 day temperature variations. No specific cause for this phenomenon is known, though these oscillations are due to water motions near the water-bottom boundary and can cause mixing as well as intensify heat release from the sediment to water. Probable cause of temperature oscillations with 1 day period is internal wave of Poincaré type. The future research therefore should be aimed at the explaining of the diurnal temperature variations.

The comparison between the rate of heat content change in a water column and the difference of vertical heat fluxes from sediment to water and from water to ice show that horizontal heat transport from shallow to deep areas can exist in rather shallow temperate lakes.

Acknowledgments The present study was supported by the Russian Academy of Sciences, The Russian Fund of Basic Research (project 07-05-00351), the Swedish Institute (VISBY Programme), and Åke och Greta Lisshed Foundation, Sweden. Author expresses her gratitude to the research team of the Northern Water Problems Institute for their heroic efforts in collecting data during winter field campaigns, for their support and contributions. Author expresses her gratitude to Prof. K. Salonen and Dr. A. Terzhevik for their detailed review of the manuscript and good advice.

References

Baehr MM, DeGrandpre MD (2002) Under-ice CO_2 and O_2 variability in a freshwater lake. Biogeochemistry 61:95–113

Bengtsson L (1996) Mixing in ice-covered lakes. Hydrobiologia 322:91–97

Bengtsson L, Svensson T (1996) Thermal Regime of Ice-Covered Swedish Lakes. Nordic Hydrol 27:39–56

Bengtsson L, Malm J, Terzhevik A, Petrov M, Bojarinov P, Glinsky A, Palshin N (1996) Field investigation of winter thermo- and hydrodinamics in a small Karelian lake. Limnol Oceanogr 41:1502–1513

Birge E, Juday C, March H (1927) The temperature of the bottom deposits of lake Mendota. Trans Wisconsin Acad Sci 23:187–231

Boylen C, Brock T (1973) Bacterial decomposition processes in Lake Wingra sediments during winter. Limnol Oceanogr 18:628–634

Gill AE (1982) Atmosphere-ocean dynamics. Academic Press, New York

Golosov S, Ignatieva N (1999) Hydrothermodynamic features of mass exchange across the sediment-water interface in shallow lakes. Hydrobiol 408(409):153–157

Golosov S, Maher OA, Schipunova E, Terzhevik A, Zdorovennova G, Kirillin G (2007) Physical background of the development of oxygen depletion in ice-covered lakes. Oecologia 151:331–340

James A (1974) The measurement of benthal respiration. Water Res 8:955–959

Kirillin G, Engelhardt C, Golosov S (2009) Basin-scale internal waves in the bottom boundary layer of ice-covered Lake Müggelsee, Germany. Aquat Ecol (in present issue)

Likens GE, Ragotzkie RA (1965) Verticla water motions in a small, ice-covered lake. J Geophys Res 70:2333–2344

Likens GE, Ragotzkie RA (1966) Rotary circulation of water in an ice-covered lake. Int Ver Theor Angew Limnol Verh 16:126–133

Litinskaya KD, Polyakov YuK (1975) Lakes of Vendurskaya group: Uros, Rindozero and Vendurskoe. In: Karelian water resources and their use. Karelian Branch of Academy of Sciences of USSR, Petrozavodsk, pp 57–66 (in Russian)

Mackenthun AA, Stefan HG (1998) Effect of flow velocity on sediment oxygen demand: experiments. J Environ Eng 124:222–230

Malm J (1998) Bottom buoyancy layer in an ice-covered lake. Wat Resour Res 34:2981–2993

Malm J, Terzhevik A, Bengtsson L, Boyarinov P, Glinsky A, Palshin N, Petrov M (1996) A field study on thermo- and hydrodynamics in three small Karelian lakes during winter 1994/1995. Department of Water Resources Engineering, Report 3197, University of Lund

Malm J, Terzhevik A, Bengtsson L, Boyarinov P, Glinsky A, Palshin N, Petrov M (1997a) Temperature and hydrodynamics in lake Vendurskoe during Winter 1995/1996. Department of Water Resources Engineering, Report 3213, University of Lund

Malm J, Terzhevik A, Bengtsson L, Boyarinov P, Glinsky A, Palshin N, Petrov M (1997b) Temperature and salt content regimes in three shallow ice-covered lakes. Nordic Hydrol 28:129–152

Malm J, Terzhevik A, Bengtsson L, Boyarinov P, Glinsky A, Palshin N, Petrov M (1998) A field study on currents in a shallow ice-covered lake. Limnol Oceanogr 43:1669–1679

Mortimer CH, Mackereth FJH (1958) Convection and its consequences in ice-covered lakes. Verh Internat Verein Limnol 13:923–932

Petrov M, Terzhevik A, Zdorovennov R, Zdorovennova G (2006) The thermal structure of a shallow lake in early winter. Wat Res 33:135–143

Petrov M, Terzhevik A, Zdorovennov R, Zdorovennova G (2007) Motion of water in an ice-covered shallow lake. Wat Res 34:113–123

Rahm L (1985) The thermally forced circulation in small, ice-covered lake. Limnol Oceanogr 30:1122–1128

Ryanzhin SV (1997) Thermophysical properties of Lake sediments and water-sediments heat interaction. Department of Water Resources Engineering, Report 3214, University of Lund

Sahlberg J (1988) Modeling the thermal regime of a lake during winter condition. Cold Reg Sci Technol 15:151–159

Stefanovic DL, Stefan HG (2002) Two-dimentional temperature and dissolved oxygen dynamics in the littoral region of an ice-covered lake. Cold Reg Sci Technol 34:159–178

Welch HE, Bergmann MA (1985) Water circulation in small arctic lakes in winter. Can J Fish Aquat Sci 42:506–520