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Merja Pulkkanen

Under-Ice Temperature and Oxygen Conditions in Boreal Lakes

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Dedicated to the most stubborn
yet warm-hearted man ever
walked on the face of the Earth,
Toivo Pulkkanen (†).

ABSTRACT

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Alternation of ice-free and ice-covered periods affects the hydrodynamics, biogeochemistry and biology of lakes. In winter, the snow and ice cover isolate the lake water from interactions with the atmosphere and low water temperatures slow down the biological processes within a lake. In this thesis, under-ice water temperature and oxygen conditions in boreal lakes were investigated to describe the hydrodynamics prevailing during winter. The weather conditions during the autumnal cooling period affected the under-ice thermal structure of Lake Pääjärvi (southern Finland), with impacts extending to the following spring. During winter, the temperature evolution of the lake with water temperature below the density maximum of fresh water, 3.98 °C, was characterized by an increase of temperature in the deepest water layers and cooling of the upper part of the water column. The results showed that the thermal structure was controlled by two heat fluxes: sediment heat flux and heat flux from water to ice. Conduction of sediment heat to the overlying water increased its density and an advective flow could be generated along the lake bottom. This resulted in the accumulation of heat and low oxygen water in the deepest location of the lake; this mechanism was found in other deep lakes with no significant through-flow in winter. After snow melt in early spring, solar radiation started to warm the upper water layers and triggered the onset of vertical convection leading to under-ice mixing. The progress of under-ice mixing at the deepest location of the lake was associated with both vertical convection and advective flow of water in the near-bottom water layers from littoral and sublittoral regions that warmed earlier. Full under-ice spring turnover was observed to be surprisingly frequent in such a deep lake as Lake Pääjärvi. The phenomenon was favoured by low (< 3 °C) temperature in the near-bottom water layers. In the emerging concern over climate change, a better understanding of the processes governing conditions in ice-covered lakes will extend the existing knowledge of the seasonal cycle of lakes.

Keywords: Advection; convection; ice cover; oxygen; temperature; turnover.

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following original articles, which will be referred to in the text by their Roman numerals I–IV. M. Pulkkanen participated in field work and laboratory analyses during 2005–2007, analysed data collected during 2004–2010 and wrote the first version of the manuscripts which were finished with the co-authors.

I Pulkkanen M., Huttula T. & Salonen K. 2013. Thermal structure of an ice-covered, deep boreal lake (Pääjärvi, southern Finland). Manuscript.

II Pulkkanen M. & Salonen K. 2013. Accumulation of low-oxygen water in deep waters of ice-covered lakes cooled below 4 °C. *Inland Waters* 3: 15-24.

III Pulkkanen M., Salmi P. & Salonen K. 2013. Under-ice circulation in a deep temperate lake. Manuscript.

IV Pulkkanen M. & Salonen K. 2013. Spatial development of under-ice mixing in a deep boreal lake. Manuscript.

1 INTRODUCTION

1.1 The ice season in lakes

The majority of the Earth´s lakes are located in the Northern Hemisphere and are covered by ice perennially or seasonally with an important contribution to the cryosphere (Downing et al. 2006, Brown & Duguay 2010). Formation of ice cover determines the type of mixing in holomictic lakes, i.e. lakes that undergo full turnover at least once per year (Boehrer & Schultze 2008). Temperate boreal and subarctic lakes with annual ice cover formation are generally dimictic, undergoing full turnover in spring and autumn (Lewis 1983). Traditionally winter has been considered to be an unimportant season in the lake ecosystem, therefore attracting less interest than summer studies even though the alternation between ice-covered and ice-free periods of lakes plays a significant role in the ecology and biogeochemistry of lakes (Baehr & DeGrandpre 2002). Difficulties in sampling during winter and spring thaw have also restricted the research.

Knowledge of under-ice events has been slow to accumulate, although some of the conditions and factors affecting them were already deduced at the beginning of the 1900s. In recent decades the concern about climate change has encouraged studies on winter limnology and drawn attention to the ice season of lakes (Salonen et al. 2009, Kirillin et al. 2012). In addition to ecological consequences, studies have been made from a socio-economic standpoint (Prowse et al. 2009). Winter conditions have attracted physicists as the hydrodynamics of ice-covered lakes differ from ice-free conditions due to the lack of wind shear (Farmer 1975, Mironov et al. 2002).

As the winter processes are slow and data are sparse, modelling has been a tool to investigate ice and water dynamics. Simulations of ice cover and water temperature have been made from the standpoint of physical limnology (e.g. Rahm 1985, Patterson & Hamblin 1988, Zilitinkevich & Malm 1993, Huttula et al. 2010, Oveisy et al. 2012), lake management and water quality (e.g. Rogers et al. 1995, Meding & Jackson 2001, Malve et al. 2005), and climate change (e.g.

Huttula et al. 1992, Fang & Stefan 1996, 1997, Elo et al. 1998, Walsh et al. 1998, Blenckner et al. 2002, Saloranta et al. 2009, Kirillin 2010, Dibike et al. 2011). Lake ecosystems both affect the climate at a regional scale and respond to climatic forcing (Krinner 2003). As the major impacts of climate change are focusing on winter and spring in boreal lakes through the fate of ice cover (e.g. Weyhenmeyer et al. 2011), more information on the governing processes during the ice-covered period in lakes is needed to assess the future challenges in lake management and possible consequences for aquatic organisms (DeStasio et al. 1996, Shuter et al. 2012). Due to the nonlinearity of the thermodynamic properties of water, the response of lakes is not easily predictable (Farmer & Carmack 1981).

1.2 Thermodynamic and optical properties of lake ice, snow and water

1.2.1 Lake ice and snow cover

Ice cover phenology (i.e. ice-on and ice-off dates) has been widely used as an indicator of global change as it is directly driven by climatic factors and affects many ecosystem services (Schröter et al. 2005, Weyhenmeyer et al. 2011). Lake and river ice phenology is well documented in Finland with uniquely long data sets (Korhonen 2006). On the other hand, ice structure observations, which determine the optical and thermodynamic properties of ice, are sparse at a spatial scale. The observations involve the thicknesses of the snow cover, congelation ice (black ice), and the superimposed ice (snow ice), which consists mainly of frozen slush (Leppäranta & Kosloff 2000), but they do not give detailed information about the spatial heterogeneity of the lake ice cover.

The ice cover on Lake Pääjärvi, in Southern Finland, was monitored for 12 consecutive years and consisted of congelation ice (black ice; either columnar or macro grained) and granular superimposed ice (snow ice), with all of the structures varying in optical properties (Leppäranta 2010). Albedo is the ratio of upwelling total irradiance to downwelling total irradiance at the surface, a measure determining the amount of radiation at the surface of ice. Arst et al. (2008) found the albedo of ice to vary between 0.20 and 0.58 in boreal lakes depending on the characteristics of ice and weather conditions. Snow cover albedo was higher (0.85–0.94), blocking most of the incident solar radiation from a lake. Thermal conductivities of ice and snow layers are low compared to water. Hence, snow cover acts as an insulator and heat conduction through ice is a slow process (Adams 1981, Bengtsson & Svensson 1996).

1.2.2 Lake water

Water density determines the stability of stratification in lakes, and local density differences generate currents (Boehrer & Schultze 2008). The nonlinear temperature dependence of fresh water density is one of the most important properties of water (Chen & Millero 1986). The temperature (T) at which fresh water exhibits maximum density, T_{md}, at atmospheric pressure and in zero salinity is 3.98 °C, and it decreases with depth at a rate of 0.002 °C m^{-1}, and with salinity at 0.22 °C ppt^{-1} (Wetzel 2001). Salinity relationships in fresh water lakes should be applied with caution, because the salt composition is different from that in seas, and may bias density equations commonly used in oceanography (Boehrer & Schultze 2008). When considering the penetrative convection involved in mixed layer deepening in autumn and spring, the pressure effect becomes significant at depths > 60 m (Farmer & Carmack 1981). Hence, equations with the pressure term should be applied when calculating densities in lakes deeper than 60 m. In the case of Lake Pääjärvi, in southern Finland, with salinity of 0.05 PSU (practical salinity unit), the mean T_{md} at a depth of 1 m (0.01 dBar) and at 85 m (0.85 dBar) are 3.970 °C and 3.955 °C, respectively. Maximum densities are 1000.016 kg m^{-3} (1 m) and 1000.057 kg m^{-3} (85 m) (Fig. 1). At T_{md} the expansion coefficient of fresh water, a, changes sign and becomes critically dependent on pressure (Farmer & Carmack 1981, Kelley 1997):

$$a = (1.69 \cdot 10^{-5}\ °\mathrm{C}^{-2}) \cdot (T - 3.95\ °\mathrm{C}) \qquad (1)$$

Because $a < 0$ for fresh water below 3.98 °C, solar radiation can cause convection in ice-covered lakes (Kelley 1997).

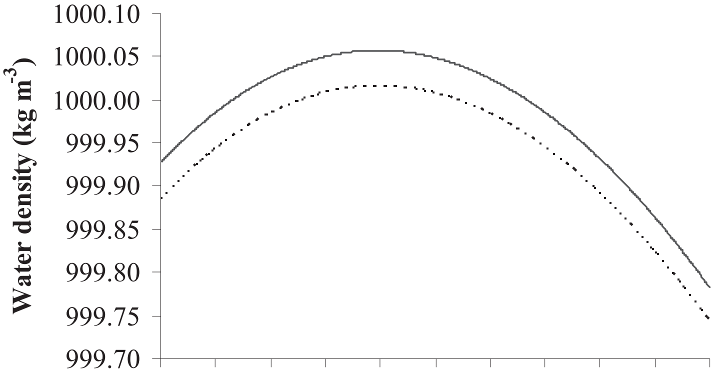

FIGURE 1 Water density (kg m^{-3}) in the temperature range of 0 – 10 °C at depths of 1 m (dashed line) and 85 m (solid line) with salinity of 0.05 PSU; atmospheric pressure not taken into account. Calculated according to Millero et al. (1980) and Millero & Poisson (1981).

The water colour affects penetration of solar radiation into the water column (Matthews & Heaney 1987). Highly humic lakes absorb solar radiation efficiently and the upper water layers warm more rapidly, but in clear water lakes the radiation can penetrate deeper. Impurities are excluded from the ice crystal structure during freezing. Therefore the melting of ice can form a layer of more transparent water under ice in spring (Belzile et al. 2002).

1.3 Seasonality of stratification and mixing patterns in lakes

1.3.1 Autumnal cooling

Stratification patterns determine the heat and gas exchange of lakes during the open water period. Dimictic lakes circulate freely during autumn and spring and are generally stratified stably in summer and weakly in winter. In autumn solar radiation decreases and lake surface water cools breaking down convectively the vertical three-layer structure of epilimnion, thermocline and hypolimnion (Malm & Zilitinkevich 1994). With decreasing air temperature and wind mixing, shallow areas cool first and currents directed to deeper areas are generated, with significant contribution to heat and matter transport between shallow and deep areas of the lake (Chubarenko & Hutter 2005).

Farmer & Carmack (1981) found three distinct phases in the autumnal cooling period based on the evolution of water column temperature in a deep lake: 1) breakdown of summer stratification at isothermal conditions slightly above the temperature of maximum density T_{md}, 2) a pressure-sensitive phase near T_{md}, and 3) restratification below T_{md}. The processes involved in restratification are mixing due to wind energy above and gravitationally unstable flow (thermobaric convection) below the depth of the water layer of maximum density (Farmer & Carmack 1981, Kirillin et al. 2012).

The autumnal isothermal period is significant in the seasonal cycle of lakes. A major part of the carbon gas emissions from lakes occurs after the breakdown of summer stratification, although some gas exchange occurs also during stratified periods due to penetrative convection within the water column (Eugster et al. 2003, Ojala et al. 2011). López Bellido et al. (2009) reported that carbon dioxide flux to the atmosphere was greater in autumn than in spring in Lake Pääjärvi. The autumnal cooling period determines the thermal structure as well as the dissolved oxygen conditions in a lake during the following winter (Hutchinson 1957, Meding & Jackson 2001).

1.3.2 Winter conditions

After the lake water temperature has decreased below T_{md}, the onset of ice cover formation depends on the air temperature, wind speed and morphometry of the lake, with depth being the most important factor (Korhonen 2006).

Observations made since the early 1900s have suggested that slow currents exist in ice-covered lakes. Indirect temperature measurements as well as acoustic measurements and tracer experiments have been used to study the under-ice current field (Mortimer & Mackereth 1958, Likens & Hasler 1962, Likens & Ragotzkie 1966, Pennak 1968, Stewart 1972, Welch & Bergmann 1985, Colman & Armstrong 1987, Ellis et al. 1991, Menemenlis & Farmer 1992, Bengtsson & Svensson 1996). Bengtsson (1996) listed four types of currents affecting the winter thermal structure of a lake: 1) currents induced by through-flow, 2) mixing induced by wind seiche, 3) currents generated by sediment heat flux and 4) mixing induced by solar radiation. Recent intensive studies of temperature, current field and oxygen conditions in Lake Vendyurskoe in Karelia, Russia, have contributed significantly to knowledge of the physical processes controlling the dynamics of shallow, ice-covered lakes (e.g. Bengtsson et al. 1996, Glinsky 1998, Malm et al. 1998, Mironov et al. 2002, Jonas et al. 2003, Terzhevik et al. 2009). The lake has a surface area of 10.4 km^2, and a maximum depth of 13.4 m. Petrov et al. (2007) concluded that, during winter, the main causes of water movements in Lake Vendyurskoe are wind-induced oscillations of ice cover and horizontal differences in the density field of water.

After the freeze over in lakes with no significant through-flow, lake water temperature is controlled mainly by two heat fluxes: heat input from the sediment and outflow to the ice cover (Bengtsson et al. 1996). Density currents induced by sediment heat flux were suggested already by Birge et al. (1927). When heat stored during summer in the sediment is gradually released to overlying water, advective density gradient currents are generated flowing along the lake slopes towards the deepest parts or the nearest local depression of the lake bottom, also accumulating low-oxygen water (Mortimer & Mackereth 1958, Welch & Bergmann 1985). Sediment heat flux in winter depends on heat absorbed during the previous summer, conditions during autumnal cooling and the constituents of the lake bottom. Bengtsson & Svensson (1996) reported heat fluxes from the sediment of several ice-covered Swedish lakes to vary annually and spatially within a lake, with a decreasing trend towards the end of the winter as the temperature difference between the sediment and overlying water diminishes. Bengtsson et al. (1996) estimated that the sediment heat flux from the lake bottom of Lake Vendyurskoe varied in a cross-section within a range of 0.6–2.0 W m^{-2} in early April.

Mineralization in winter and the impacts of physical, chemical and biological processes on the concentrations of two main indicators of lake water quality, dissolved inorganic carbon (DIC) and especially dissolved oxygen (DO), are still poorly investigated and neglected in metabolic studies of lakes (Hanson et al. 2006, Karlsson et al. 2008). In winter, aerobic metabolism is governed by the amount of oxygen dissolved in lake water during autumnal turnover, the amount and rate of the decomposition of organic matter, and the length of snow and ice cover on the lake (Meding & Jackson 2001). The organic matter can be 1) mineralized in the water column, 2) mineralized in the surface sediment, 3) stored as reduced or potentially oxidizable matter, or 4) mineralized by fermentation (Charlton 1980). Most of the mineralization processes occur in lake sediments (Jonsson et al. 2001).

1.3.3 Spring conditions

One of the first observations of under-ice vertical convection due to absorption of solar radiation was made by Birge (1910). The mechanism causing vertical convection was studied in detail by Farmer (1975), Mironov et al. (2002) and Jonas et al. (2003). Based on detailed water temperature measurements below the ice cover of a shallow lake, Jonas et al. (2003) determined five distinct layers within a lake water column undergoing convection: 1) conduction, 2) diffusive, 3) convective, 4) interfacial entrainment and 5) quiescent layers. According to their observations on daytime stratification dynamics, absorption of solar radiation causes density instabilities in the convective layer and water is transported downward to the entrainment layer and further to the quiescent layer. Absorption of solar radiation in the conduction and diffusive layers follow diurnal dynamics and water is moving either upwards or downwards depending on the salinity and temperature gradient caused by cold water entrainment from the convective layer below and water from melting ice above. Under-ice convection differs from convection due to surface cooling in that the buoyancy flux is not produced in the surface but within the convective layer itself, reducing the kinetic energy available for mixing (Jonas et al. 2003). For instance, Forrest et al. (2008) reported an under-ice convective layer in Pavilion Lake (Canada, maximum depth 61 m) deepening at a slow rate of 1.14 m d^{-1} with a warming rate of 0.015 °C d^{-1}.

Full spring turnover in lakes is commonly assumed to take place after the complete ice-off (Wetzel 2001). In large lakes the earlier warming of littoral regions may lead to a thermal bar phenomenon between the shallow and deep regions of the lake (Mortimer 1974); one of the first records of this was by Forel (1895). In general terms this is called cabbeling (Kay 2001). When two water masses at different temperatures form a mixture of water with a higher density than in the original components, the density barrier prevents the mixing between different parts of a lake.

Both spring and autumn periods are important phases in the seasonal cycle of lakes due to the direct impact on the greenhouse gas emissions to the atmosphere. Due to the ice cover, carbon and nitrogen gases produced in lakes accumulate during winter. These greenhouse gases are released to the atmosphere after mixing of the lake water column and ice-off (e.g. Striegl & Michmerhuizen 1998, Huttunen et al. 2003a, Huttunen et al. 2003b, López Bellido et al. 2009).

1.4 Lake ecosystem challenges in a future climate

The climatic variations in the Northern Hemisphere can be linked, to a certain degree, to the North Atlantic Oscillation, NAO (George et al. 2004). Although there is temporal coherence in lakes of the same region, generalisation of the impacts depends on lake characteristics (Järvinen et al. 2002). The potential impacts of climate change on ecosystems have been studied with long-term time series analysis, empirical studies, and by model simulations (Blenckner 2005). Some of the key response variables in lakes used as indicators of climate change are water temperature, ice phenology, chemical variables and biota (Adrian et al. 2009).

Global mean air temperature is predicted to increase by 1.3 °C to 1.8 °C towards the mid-century (2046–2065) (Meehl et al. 2007). Estimated shifts in climatic zones in Europe are likely to have complex impacts on water resources (Jylhä et al. 2010). Jylhä et al. (2004) reported that the annual mean temperature and annual mean precipitation in Finland are projected to rise by 1.8–5.2 °C and 1–28 % by the 2050s compared to the baseline period of 1961–1990. In a seasonal perspective, increase in air temperature was indicated to focus on winter (December-February) and spring (March-May) by an increase of 2.0–7.8 °C and 1.5–7.8 °C, respectively. Precipitation was projected to increase during winter, spring and autumn (September-November).

The predicted increase in air temperature during summer will likely change the stratification patterns in lakes (King et al. 1999). The impact on the temperature distribution of the water column depends on the lake; the hypolimnion of thermally stratified small lakes may be sheltered from increasing air temperature due to increased thermal stability, while in large lakes where wind fetch is large enough to allow effective mixing, the temperature of the hypolimnion can increase (Blenckner et al. 2002). Variations in mixing patterns during the open water period can occur as the stability of the water column changes (MacIntyre et al. 2009). In addition to atmospheric forcings, also changes in catchment areas and land use will affect the response of a lake. For instance, a change in runoff water colour due to increase in precipitation and dissolution of humic substances will affect the absorption of solar radiation within a lake water column and may alter the structure of stratification in small lakes (Houser 2006). Extreme events in the present climate can give some information on the adaptation capacities of lake ecosystems, but the situation may be different when the conditions persist for longer with possible combined effects (Rempfer et al. 2010). On the other hand, climate-induced variations in the response of lakes have occurred in the past, and examination of the impacts of past extreme conditions can suggest possible consequences of future changes to lake ecosystems (Benson et al. 2012).

2 OBJECTIVES

The main objective of this study was to investigate the evolution of thermal structure in a deep, boreal lake during the cooling period in autumn and during the ice-covered period in winter and spring. Secondly, oxygen conditions in five ice-covered boreal lakes which differed in morphometry and water colour were explored. In the annual cycle of dimictic lakes these phases are clearly under-investigated and many of the impacts accompanying climate change are predicted to focus on the ice season of lakes. More specifically, the following aspects were studied:

a) Thermal conditions affecting water movements in oligo-mesotrophic and mesohumic Lake Pääjärvi (southern Finland) during winters 2004/2005–2009/2010 (I)

b) Evolution of temperature, under-ice DO and DIC concentrations and water movements in deep, morphologically variable lakes in winters 2003/2004–2005/06 (II)

c) Evolution of under-ice mixing depths and spring full turnover at the deepest location of Lake Pääjärvi during springs 2004–2010 (III)

d) Development of under-ice horizontal temperature field and spatial mixing in Lake Pääjärvi in spring 2004 and 2006 (IV)

3 STUDY LAKES AND METHODS

3.1 Study lakes

The thermal structure and DO as well as DIC conditions were investigated in five deep Finnish lakes (Table 1), focusing on Lake Pääjärvi. Lakes Iso-Roine, Pyhäjärvi (Orimattila) and Pääjärvi are located in southern Finland, Lake Päijänne in central Finland and Lake Kilpisjärvi in north-western Finland (Fig. 2). Except for Lake Iso-Roine, the mean depths of the lakes were generally higher than the average depth (7 m) for Finnish lakes (Kettunen et al. 2008). The morphological characteristics of the lakes are presented in detail in II.

TABLE 1 Basic characteristics of the study lakes (ND: no data).

Lake	Location	Elevation	Surface area	Mean depth	Maximum depth	Retention time
	(WGS-84)	(a.s.l., m)	(km^2)	(m)	(m)	(years)
Iso-Roine	61° 12′5 N					
	24° 35′6 E	84	31	7.2	73	ND
Päijänne	62° 02′8 N					
	25° 50′0 E	78	141	15.6	94	3.3
Pyhäjärvi	60° 42′9 N					
	26° 00′4 E	40	13	20.8	68	ND
Pääjärvi	61° 03′4 N					
	25° 07′5 E	103	13	14.8	85	3.3
Kilpisjärvi	68° 56′2 N					
	20° 50′8 E	473	37	19.5	57	8.0

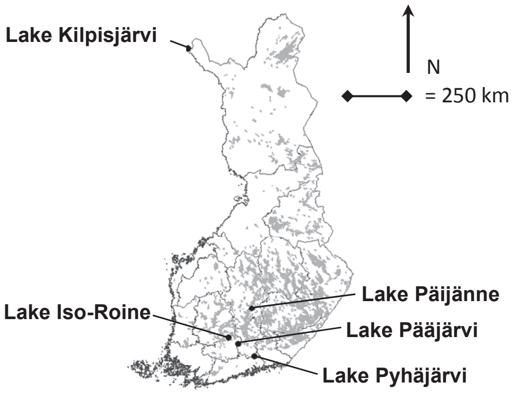

FIGURE 2 Locations of the study lakes in Finland.

3.2 Data and methods

3.2.1 Meteorological and hydrological data

Air temperature and ice phenology data were obtained from Lammi Biological Station (University of Helsinki) adjacent to Lake Pääjärvi. Lake ice thickness and snow depth were measured by the Finnish Environment Institute every ten days from the western bay of Lake Pääjärvi, except at the onset of ice-on and ice-off periods. Wind speed data from Hämeenlinna weather station 40 km south-west from Lake Pääjärvi were provided by the Finnish Meteorological Institute. Daily global radiation data were obtained from the observatory of Jokioinen, the Finnish Meteorological Institute, 100 km south-west from Lake Pääjärvi. Lake water temperature and colour data in winter (March or April) and inflow and outflow river discharge data were obtained from the Hertta database of the Finnish Environment Institute with supplementary information on all the study lakes.

3.2.2 Water temperature measurements

Water temperature was measured from the deepest observed location of Lake Pääjärvi with Starmon Mini temperature recorders (Star-Oddi, Iceland; accuracy ± 0.05 °C, average resolution 0.013 °C) at 1 h (winter 2004) or 0.5 h intervals from early October to early May (2004/2005–2009/2010) (Table 2). In the other study lakes the measurement period focused on winters 2004/2005 and 2005/2006. The recorders in the water column were installed at 5 m (except at 1 m) depth intervals down to the lake-specific bottom depth at the deepest observed location of the study lakes. In Lake Pääjärvi, water temperature was measured with the same depth intervals from several locations (IV).

3.2.3 Dissolved oxygen and dissolved inorganic carbon determinations

Samples for dissolved oxygen (DO) and dissolved inorganic carbon (DIC) were taken with a Limnos tube sampler from the same depths as the temperature records into ground glass stoppered bottles (Table 2). Samples were kept in slush ice before determination. The DO concentration in the samples was determined by a modified Winkler method with a Mettler Toledo DL53 Titrator (Mettler-Toledo International). In spring 2005 an Aanderaa Oxygen Optode 4175 sonde (Aanderaa, Norway; accuracy < 8 μmol l^{-1} and resolution < 1 μmol l^{-1}) was used in Lake Pääjärvi. The sonde was attached to a conductivity, depth and temperature meter (AML Micro-CTD, Canada). The results were occasionally calibrated with samples determined by the Winkler method. The DIC concentration in the samples was determined by an acidification and bubbling method using infrared detection of CO_2 (Salonen 1981). When the ice was too weak to walk on, a hydrocopter (courtesy of Tvärminne Zoological Station, University of Helsinki), was used to access the sampling locations.

TABLE 2 Temperature measurement (N_l: number of temperature measurement locations within a lake, N_r: the total number of used temperature recorders), and DO and DIC sampling (N_d: sampling depths, N_{DO} and N_{DIC}: sampling times of DO and DIC, respectively) details during winters 2003/2004–2009/2010.

Lake	Winter	Temperature measurements		DO and DIC sampling		
		N_l	N_r	N_d	N_{DO}	N_{DIC}
Iso-Roine	2003/2004	-	-	14	1	1
	2004/2005	-	-	14	2	2
Kilpisjärvi	2004/2005	1	10	10	2	2
	2005/2006	1	10	-	-	-
Pyhäjärvi	2003/2004	-	-	14	1	1
	2004/2005	-	-	14	2	2
	2005/2006	1	14	14	2	2
Päijänne	2003/2004	-	-	19	1	1
	2004/2005	1	19	19	2	2
	2005/2006	-	-	-	-	-
Pääjärvi	2003/2004	4	33	16	3	3
	2004/2005	1	16	16	4	4
	2005/2006	3	24	16	5	3
	2006/2007	1	16	-	-	-
	2007/2008	1	16	-	-	-
	2008/2009	1	16	-	-	-
	2009/2010	1	16	-	-	-

4 RESULTS AND DISCUSSION

4.1 Temperature and dissolved oxygen conditions in winter

4.1.1 Autumnal cooling in Lake Pääjärvi

The autumnal cooling period determines the under-ice thermal structure of lakes (Hutchinson 1957), and the amount of oxygen which is available during winter (Greenbank 1945, Meding & Jackson 2001). During the study years, the autumnal turnover started in Lake Pääjärvi with the cooling of the upper part of the water column (I). The lake became isothermal at 4.8–5.8 °C during the autumns 2004–2009 (Table 1 in I). After the mixed layer reached the lake bottom, the lake continued to cool until ice-on. The temperatures reached at the time of ice-on were below the density maximum of Lake Pääjärvi, which suggests that the deep water cooling was associated with thermobaric convection. The longest time (75 days in 2006/2007) from the full autumnal turnover to ice-on was about three-fold to the shortest time (27 days in winter 2004/2005). In five of the six study years, the minimum temperature at the depth of 75 m was reached before or at the day of ice-on. In the winter 2004/2005 the minimum temperature was observed more than two weeks before ice-on. The mean daily water temperature in the whole water column of Lake Pääjärvi varied from 1.2 °C (SD ± 0.66) to 2.8 °C (SD ± 0.07) on the day of minimum temperature in the depth of 75 m.

Based on temperature measurements in Lake Pääjärvi, the full turnover began in autumn 2005 on 21st November (I). At that time, the vertical distributions of dissolved substances became uniform. The evolution of DO concentration was followed during December 2005, and the vertical profile of DO was almost uniform with a range of 11.4–11.5 mg l^{-1} (SD ± 0.03) between the bottom (at 75 m depth) and surface (at 1 m depth), respectively, on 1st December (II). Two days before ice-on, on 20th December, the DO concentration varied with a range of 12.6 mg l^{-1} at the surface and 12.0 mg l^{-1} at the bottom (SD ± 0.22) (unpublished data), and then started to decrease in the deep water.

The estimation of under-ice DO and DIC dynamics with intermittent determinations was based on the fact that during the autumnal cooling period the concentrations are uniform, and changes in the concentrations are due to both winter respiration and under-ice hydrodynamics (II).

The predicted increase in summer air temperature may emphasize the significance of autumn in the seasonal cycle of lakes, with impacts on the following growing season. Autumnal increase in air temperature may delay the cooling period and the timing of ice-on (Korhonen 2006, Saloranta et al. 2009). The thermal structure of Lake Pääjärvi at the end of the autumnal cooling period affected the depth of the under-ice mixed layer in the following spring (III). The mean temperature of the mixed layer at the time of ice-off varied between the study years (2.3–3.5 °C) and showed a significant correlation ($r = 0.75$, $p = 0.05$) with the temperature at 75 m before the impact of convection (Fig. 2 in III).

4.1.2 Winter water temperature in Lake Pääjärvi

In the study years, the thermal structure of Lake Pääjärvi was either relatively evenly distributed within the whole water column or showed steep temperature gradients, especially in the upper part (< 30 m depth) of the water column. In the winters 2004/2005, 2005/2006 and 2009/2010 the water column temperature varied from 0.0 (underside of ice) to 3.3 °C in the near-bottom layer (Fig. 5 in I). In the winter 2007/2008 the water temperature varied with the smallest range from 0.0 to 2.0 °C. During mid-winter, the water temperature at the deepest location of Lake Pääjärvi decreased in the upper water layers (1–10 m depth), remained quite stable in the middle (30–40 m depth) and increased in the lower (> 50 m) water column (I). In the winter 2003/2004, Jakkila et al. (2009) found the heat flux from water to ice to be 5 W m^{-2}. The energy released from the cooling of the upper water layers led to ice growth and, to a small extent, heat conduction through ice to compensate the net heat loss due to terrestrial radiation.

The long-term (1965–2011) mean water column temperature in March-April in the deepest location of Lake Pääjärvi was 2.4 °C (SD ± 0.9 °C) with positive, but not significant trend in the time series (linear model, $t = 1.289$, $p = 0.205$) (Fig. 4a in I). The water temperature in the upper (1-30 m) part of the water column was lowest in 1967 (mean 0.8 °C) and highest in 1991 (mean 2.6 °C). The water temperature in the lower (40 - 80 m) part of the water column was lowest in 2008 (mean 2.1 °C) and highest in 1999 (mean 4.0 °C). No significant trend in the evolution of surface water (1–20 m) or bottom water (60–80 m) temperature was found, although the trend was positive both for surface water ($t = 1.266$, $p = 0.213$) and for bottom water ($t = 1.139$, $p=0.261$; Fig. 4b and c in I). These results are in accordance with Arvola et al. (2010), who reported a weak rising trend in winter water temperatures during the past few decades across Europe. A slight positive trend in surface water temperatures can actually reflect the earlier onset of spring warming, and not necessarily warmer winter temperatures.

After the minimum water temperature reached in autumn, the near-bottom water temperature started to increase, and in winter 2004/2005 the rate of increase was at first most rapid. In the first five days of the warming period of the near-bottom water, the temperature increased almost 0.1 °C d^{-1}. Also in the winter 2009/2010 the warming rate was high (0.04 °C d^{-1}) for the first five days. The warming rate slowed down towards the end of the ice-covered period (one week before ice-off) and varied from 0.002 to 0.005 °C d^{-1} between the years. The annual increase in the under-ice temperature at the depth of 75 m varied from 0.3 to 0.5 °C. Because the water temperature in the whole lake was generally below 3.98 °C, the small heat flux from sediment generated advective density gradient currents flowing towards the deepest location and heat was accumulated. Under-ice temperatures are therefore higher in mid-winter than at the time of ice-on in many lakes (Bengtsson & Svensson 1996).

The results showed that the mid-winter thermal structure of Lake Pääjärvi was controlled by the slow heat fluxes from the sediment to the overlying water and from water to the ice (Fig. 3). Two other possible heat fluxes, groundwater and river inflow, were estimated to be negligible during winter (I, II). Huttula et al. (2010) applied the three-dimensional Princeton Ocean Model to estimate under-ice water movements in Lake Pääjärvi in winter 2004. The results suggested that sediment heat flux together with the Coriolis force generated lake-wide horizontal water movements that had opposite directions in the upper and lower layers of the lake. The model simulation results suggested that slow horizontal currents in near-bottom water layers directed to the deepest water and an upward directed current in the centre of the lake were prevailing under the ice cover, and this was supported by the temperature measurements.

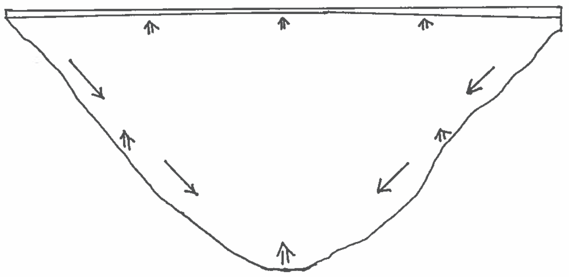

FIGURE 3 Simplified schematic figure showing the winter heat fluxes (arrow with double line) affecting water temperature and the associated water movements (advective flow, arrow with single line).

Saloranta et al. (2009) simulated future thermodynamic changes in lakes of different depth. The predicted changes towards higher autumnal and winter air temperatures together with shortening of the ice-covered period may in fact lead to cooling of deep lakes in winter. As the change in water density after heat absorption will be greater when the water is colder, this may lead to stronger under-ice water movements. Whether the predicted increase in air temperature in summer will lead to increased sediment temperature depends on the mixing conditions and duration of the cooling period in autumn. If the sediment remains markedly warmer than the water, the increased heat flux will strengthen the under-ice hydrodynamics (Bengtsson 2011).

4.1.3 Winter oxygen conditions in morphologically variable lakes

In addition to heat accumulation, advective currents caused by sediment heat flux were found to accumulate water with low oxygen concentration to the deepest water layers of ice-covered lakes with no significant through-flow (II), as found by Mortimer & Mackereth (1958). In mid-winter, the DO saturation decreased down to 50–60 % in the vicinity of the sediment, while in the upper part of the water columns it remained close to 90 % in all study lakes (Fig. 4 in II).

To characterize the relative changes in DO and DIC concentrations in the upper and lower water layers in the study lakes, a lake-specific reference depth to which to compare the determination results was used. At that depth the changes in DO and DIC concentrations as well as in water temperature were found to be minimal during the winter (negligible photosynthesis and effect of sediment warming). In lakes Iso-Roine, Pyhäjärvi and Pääjärvi the reference depth was 30 m, in Lake Kilpisjärvi 20 m and in Lake Päijänne 40 m.

In the upper part of the water column of all the study lakes, the ratio between the observed and reference depth DO and DIC concentrations was generally relatively stable and close to 1 (Figs. 5–7 in II). Below the reference depth, the ratio started to change, and in lakes Pyhäjärvi, Päijänne and Kilpisjärvi the change was most pronounced within the deepest 5–15 m of the water column. In Lake Pääjärvi, the decrease of DO and increase of DIC concentration occurred in a thicker (ca. 25 m) layer. In Lake Iso-Roine the situation was different from the other lakes, because the measurement site was near to an inlet from an upstream lake, and hence the vertical distributions of DO and DIC were probably affected by inflow, and remained similar throughout the winter indicating significant water exchange.

Length of the autumnal cooling period and the onset of freeze-over determine the winter oxygen conditions in lakes. Delay in ice-on will improve the oxygen conditions, but if the ice cover formation occurs early after a warm summer, consequences may be dramatic for aerobic organisms. In oligo- and oligo-mesotrophic lakes most of the respiration occurs in the sediment. Sediment respiration is strongly temperature-dependent: increase in sediment temperature can result in increased bacterial metabolism (Boylen & Brock 1973), and decrease the under-ice DO concentration of water, while low sediment temperature limits respiration (Bergström et al. 2010, Gudasz et al. 2010). Water movements on the sediment surface can also affect the sediment oxygen consumption. Mackethun & Stefan (1998) found that an increase in bottom velocity from 1 cm s^{-1} to 3 cm s^{-1} increased sediment oxygen demand two to three-fold. The sediment surface area is an important zone for both physics and biogeochemistry of lakes by the influence of bottom currents and the exchange of solutes and particles between sediment and water (Lorke et al. 2003, Wüest & Lorke 2003). In this study, the sediment processes were found to have an impact on both the thermal and oxygen conditions during winter.

4.2 Spring water temperature and dissolved oxygen conditions in Lake Pääjärvi

4.2.1 Under-ice temperatures and mixing

By the end of winter the snow cover on lake ice melts and solar radiation can penetrate into the water (e.g. Farmer 1975, Matthews 1988). In this study, warming of the upper water layers was found during all years well before ice-off, indicating that vertical convection can start under-ice in Lake Pääjärvi (I, III). In some years, the warming of water at 1 m depth at the deepest location started before the snow cover had melted on the ice in the western bay of the lake (the site of snow and ice measurements), which may have been due to uneven distribution of snow on ice. In addition, under-ice turnover was surprisingly frequent even in a deep lake such as Lake Pääjärvi; full under-ice turnover occurred in three of the seven study years (III).

During the last four weeks of ice in spring 2004–2010 in Lake Pääjärvi, the water temperature at a depth of 5 m increased by 0.8–1.6 °C reaching 2.3–3.5 °C at ice-off (III). As the temperature throughout the water column remained well below 3.98 °C, warming at the surface resulted in convective mixing; isothermal layer of water which progressively penetrated deeper. In the winter with the highest deep water temperature before convection (3.5 °C in 2010), the convective layer was approximately 40 m deep at the time of ice-off. In two other winters having deep water temperature greater than 3 °C, the convective layer reached depths of 50–60 m. In contrast, in the three years having the coldest bottom water (2.2–2.7 °C in 2004, 2007 and 2008) mixing extended down to the bottom 2–8 days before ice-off, indicating under-ice turnover. Hence, the deep water temperature (i.e. strength of the inverse stratification) affected the depth of the under-ice convective layer.

The measurements also showed that vertical convection was not the only mechanism for water transport between the upper and lower layers in the lake in spring (III, IV). In the shallow regions of the lake the water column became isothermal three to two weeks before ice-off, and under-ice mixing along the measurement transect was associated with both vertical convection and advective flow of water along the bottom slope in Lake Pääjärvi (Fig. 4).

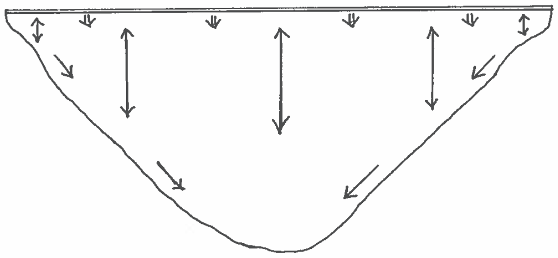

FIGURE 4 Simplified schematic figure showing the spring water movements and heat fluxes (arrow with double line) affecting water temperature; advective flow along the bottom slope (arrow with single line) and vertical convection (double arrow).

This was seen in the vertical temperature distribution at the deepest location: when vertical convection reached roughly 25 m 6–10 days before ice-off, the deepest part of the mixed region developed a temperature anomaly up to 0.3 °C higher than the upper, more uniform, region of convection (III). Along with the deepening of the convective layer, this positive temperature anomaly moved downwards and, in 2004, 2007 and 2008, it reached the bottom in the deepest part of the lake before ice-off. The most intense heating occurred in shallow water, where the solar radiation is absorbed and mixed through a smaller water column. Once the convective layer was deep enough to reach the bottom in shallow regions, the warmer and therefore denser water flowed from the shallow areas towards the deepest part of the lake (Stefanovic & Stefan 2002, IV).

The structural development of lake ice cover is the key factor determining the physics of ice-covered lakes in spring (Jakkila et al. 2009). Spatial differences and diurnal changes in the surface of ice cover affect the amount of solar radiation warming the water below ice (Adams 1981, Jakkila et al. 2009), which causes the vertical convection leading to the spring turnover of lakes. The combined effects of ice and snow cover thickness and composition as well as the radiation on surface water warming was seen when comparing the study years 2004 and 2006 in Lake Pääjärvi (IV); the snow cover existed longer and the superimposed ice layer was thicker in 2006, restricting the penetration of solar radiation at least in the fourth last week of the ice cover. The amount of radiation increased during the two last weeks of the ice cover, which led to the rapid warming of the water.

Although the annual variation in both climatic factors and lake response is large, the impacts of global change on ice cover duration and structure are already noticeable. A trend of delay in ice-on and earlier ice-off in the Northern Hemisphere was found in ice formation and thawing records from 1846 to 1995 (Magnuson et al. 2000). However, Korhonen (2006) reported that, with a few exceptions in southern Finland, the ice cover thickness on Finnish lakes has actually increased during the last 40 years. Because of the higher winter air temperatures and the increase in precipitation during the past four decades, the increase is associated with thickening of the superimposed ice layer. Some climate models have projected further increase in precipitation during winter in Finland (Jylhä et al. 2004), which has a two-fold effect on the warming of lake water at the beginning of thaw: more cloudy conditions and generation of ice with higher albedo both limit the radiation penetrating into water. As the ice-off is mostly determined by air temperature (e.g. Vavrus et al. 1996) and solar radiation, which is probably not affected by climate change (Kirillin et al. 2012), the increase in air temperature seems likely to determine the timing of ice-off in future.

The greatest seasonal increase in water temperature is predicted to focus on spring in the future due to higher spring air temperatures and earlier ice-off (Saloranta et al. 2009). Water temperature determines the onset of hatching in autumn-spawning fish species (Valkeajärvi 1988, Urpanen et al. 2005). While the lake is still ice-covered in its central region, the water in the shallow regions can be fully mixed and warmed rapidly due to both solar and, after the ice cover has melted from above, also thermal energy input. For instance the hatching of autumn-spawning coregonids is well synchronized with the ice-off (Karjalainen et al. 2002, Urpanen et al. 2005) and their hatching is likely triggered by the advective flow of warm water from the littoral zone to their spawning sites in the shallow areas. Under-ice water movements determine the phytoplankton production and species composition (Matthews & Heaney 1987, Kelley 1997). The advective flow close to the lake bottom affected the vertical distributions of phytoplankton in the deepest location of Lake Pääjärvi (Vehmaa & Salonen 2009).

4.2.2 Effects of spring mixing on dissolved oxygen conditions

DO conditions in Lake Pääjärvi were changing from the mid-winter situation while the lake was still ice-covered. In the middle of April 2004, the initial DO concentration was 11.5–12.0 mg l^{-1} down to the depth of 50 m and decreased towards the bottom. The observed minimum DO concentration at 75 m depth was 6.7 mg l^{-1} on 20th April. As the mixing extended to the bottom of the lake, DO concentration increased to 11.5 mg l^{-1} on 25th April and became uniform (mean 11.8 mg l^{-1}, SD ± 0.04) through the whole water column two days before ice-off (Fig. 4a in III). In mid-April 2005, the DO concentration decreased from 10.6 mg l^{-1} (SD ± 0.25) in the upper part (1–30 m) of the water column to 4.9 mg l^{-1} (SD ± 1.20) in the lower part (65–75 m) (Fig. 4b in III). At the end of April the DO concentration increased at 30–60 m depth, but near the bottom it was still low two days before ice-off, indicating that convection did not reach the bottom.

In spring the nutrients accumulated over winter become available for the next growing season in lakes (Baehr & DeGrandpre 2004). Under-ice mixing affects the distribution of dissolved substances even before the ice-off, and for instance, DO concentration can become uniform in the whole water column if the lake undergoes under-ice turnover, as in 2004, 2007 and 2008 in Lake Pääjärvi (III). In addition to nutrients, carbon and nitrogen gases accumulate during winter. Under-ice mixing may affect the vertical and horizontal distribution of different substances and also have an effect on the biogeochemical processes through changes in DO conditions.

According to this study, low water temperature favours the occurrence of under-ice turnover, which can relieve DO conditions in lakes with hypoxia while the lake is still ice-covered. In eutrophic lakes with more severe DO depletion in the bottom water layers, under-ice mixing can lead to a decrease in DO through the whole water column. Further, if the lake stratifies soon after ice-off, the wind action in mixing is restricted and gas exchange between water and atmosphere may remain limited. The higher spring water temperature may accelerate the overall metabolism of the lake ecosystem and can have direct adverse effects on the biota of lakes, e.g. fish species adapted to cool water conditions (Shuter et al. 2012). Timing of the water warming is of importance to the response and adaptation of cold water species. As lakes both affect the climate and respond to climate change, more detailed knowledge about the under-ice conditions can assist in future lake management.

5 CONCLUSIONS

The emerging concern about climate change has drawn attention to the ice season of lakes, mainly because under the predicted higher winter air temperatures, the fate of the ice cover will determine the degree of change in lake ecosystems.

The aim of this thesis was to study the under-ice temperature and dissolved oxygen conditions and the associated under-ice water movements in deep, boreal lakes. The weather conditions during the autumnal cooling period determined the under-ice thermal structure of Lake Pääjärvi, with impacts also on the following spring. The thermal structure of the lake below the temperature of maximum water density was controlled by two heat fluxes; sediment heat flux and heat flux from water to ice. Advective currents generated by sediment heat flux accumulated heat and low-oxygen water to the deepest water layers, a process found also in other study lakes with no significant through-flow in winter. The temperature difference between sediment and overlying water will determine the strength of under-water movements near lake bottom, which affect both the thermal and oxygen conditions in ice-covered lakes in mid-winter.

After snow melt in spring, solar radiation can warm the upper water layers, and trigger the onset of vertical convection leading to under-ice mixing. Under-ice mixing was associated to both vertical convection and advective flow of water along the bottom slope from the shallow regions which became isothermal earlier. Both of these water movements affected the under-ice thermal structure and oxygen conditions at the deepest location of the lake. Full under-ice turnover was surprisingly frequent in such a deep lake, occurring in three springs during a seven year-study. The predicted increase in autumnal air temperatures may lead to decreased winter water temperatures and enhance oxygen conditions with shortened ice-covered period. The increase in lake water density due to warming is more pronounced at low water temperatures which may lead to stronger under-ice water movements in spring.

Some of the predicted changes associated with climate change are already noticeable, although annual variation in weather conditions and the thermal structure of lakes is relatively large. Winter research will benefit from recent advances in measurement techniques and the development of reliable and weather-proof equipment. Direct measurements of slow under-ice currents allow better predictions of the hydrodynamics in ice-covered lakes. Year-round measurement platforms with weather stations on the lake itself will advance knowledge of the factors affecting the seasonality of lakes. The spatial and temporal heterogeneity in the structure of the ice cover and sediment heat flux underline the need for data collection from different locations across the lake. To fully comprehend the factors governing under-ice processes, a combination of physical, biogeochemical and biological perspectives are needed. In addition to field studies, long-term data analysis and modelling are complementing the knowledge of the impacts on lake ecosystems of a changing climate.

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In Toivola,
21st February 2013

YHTEENVETO (RÉSUMÉ IN FINNISH)

Boreaalisten järvien jäänalaiset lämpötila- ja happiolosuhteet

Limnologinen tutkimus on viime vuosikymmeniin saakka keskittynyt avovesikauteen, vaikka suuri osa pohjoisen pallonpuoliskon järvistä on jäätyneenä ainakin osan vuodesta. Avovesikauden ja jääpeitteisen ajan vuorottelu vaikuttaa merkittävästi järvien kerrostuneisuuden ja sekoittumisen kautta niiden biogeokemiaan ja biologiaan. Järvet toimivat alueellisella tasolla ilmaston säätelijöinä, ja toisaalta ilmasto vaikuttaa järvissä tapahtuviin prosesseihin. Vesiensuojelun ja hallinnoinnin perustaksi tarvitaan lisätietoa myös vähemmän tutkituista jääpeitteisen ajan prosesseista järvissä.

Tämän työn tarkoituksena oli tutkia lämpötilamittausten avulla suomalaisittain suurten ja syvien järvien jääpeitteenalaista lämpötilajakaumaa ja siihen vaikuttavia tekijöitä. Tutkimuksen pääkohteena oli Suomen neljänneksi syvin järvi, Lammin Pääjärvi Etelä-Suomessa. Meso-oligotrofisen ja mesohumuksisen järven lämpötilaa seurattiin syksystä alkukevääseen vuosina 2004–2010. Lisäksi veteen liuenneen hapen ja epäorgaanisen hiilen pitoisuuksia seurattiin morfologialtaan ja ravinnetasoltaan erilaisten järvien syvänteissä talvina 2004–2006. Etelä-Suomessa tutkimuskohteina olivat Pääjärven lisäksi Iso-Roine ja Orimattilan Pyhäjärvi, Keski-Suomessa Päijänteen Ristinselän syvänne ja Pohjois-Suomessa subarktinen Kilpisjärvi.

Syyskierron aikaan suurten, tuulelle alttiiden järvien lämpötila voi laskea huomattavasti alle makean veden maksimitiheyden lämpötilan, 3,98 ^{o}C. Tällöin veden tiheys kasvaa sen lämpötilan noustessa, millä on merkittävä vaikutus jääpeitteisen ajan hydrodynamiikkaan järvissä. Tässä tutkimuksessa syksyn jäähtymiskauden vaikutus järven lämpötilajakaumaan oli nähtävissä vielä alkukevään mittauksissa. Useina vuosina järven pohjanläheisen veden lämpötila saavutti minimiarvonsa jo ennen järven jäätymistä. Syvänteen minimilämpötilan aikaan koko vesipatsaan keskilämpötila vaihteli eri vuosina 1,2 °C:sta 2,76 °C:een, minkä jälkeen sedimentistä vapautuva lämpö nosti pohjanläheisen vesikerroksen lämpötilaa. Tällöin kehittyvän advektiivisen virtauksen havaittiin kerryttävän lämpöä kohti järven syvännettä. Talven kuluessa sedimentin lämmittävä vaikutus tasoittui sedimentin ja sen yläpuolisen veden lämpötilaeron pienetessä, ja eri vuosina syvänteen lämpötila nousi syksyn minimilämpötilasta kevätkierron alkuun 0,2–0,5 °C. Toinen havaittu muutos veden lämpötilajakaumassa oli järven pintaosien jäähtyminen. Pintaosien lämpötilassa oli pohjaosia suurempaa vaihtelua, ja lämpötila oli useana vuonna voimakkaammin kerrostunut.

Veden happipitoisuus on yksi tärkeimmistä järvien veden laatuun vaikuttavista tekijöistä. Talvisin lumi- ja jääpeite eristävät veden ilmakehän kaasunvaihdolta ja yhteyttäminen on hyvin rajallista valonpuutteen takia. Järven jäänalainen happitilanne riippuu syyskierron aikaan veteen liuenneen hapen määrästä ja metabolian voimakkuudesta. Oligotrofisissa ja meso-oligotrofisissa järvissä pääosa hengityksestä tapahtuu sedimentissä. Syyskierron aikana lämpötilan lisäksi myös liuenneiden aineiden pitoisuudet tasoittuvat koko vesipatsaassa. Tässä tutkimuksessa talviajan muutosten oletettiin johtuvan jäänalaisista virtauksista hapen kulumisen ollessa hidasta trofiatasoltaan alhaisissa järvissä. Tutkimuksessa verrattiin eri järvien liuenneen hapen ja epäorgaanisen hiilen pitoisuuksia pitoisuuksiin syvyydessä, jossa yhteyttämisen ja sedimentin lämmittävän vaikutuksen johdosta tapahtuvan happipitoisuuden ja veden lämpötilan muutoksen havaittiin olevan talven aikaan pienimmillään. Lämpötilan nousu sekä happipitoisuuden lasku ja epäorgaanisen hiilen pitoisuuden kasvu tämän syvyyden alapuolella Kilpisjärvessä, Pyhäjärvessä, Päijänteen Ristinselällä sekä Pääjärvessä viittaavat siihen, että advektiivinen virtaus kerryttää lämmön lisäksi myös vähähappista vettä järvien syvänteisiin keskitalvella. Iso-Roineella hapen ja epäorgaanisen pitoisuuden talviajan kehitykseen havaittiin vaikuttavan yläpuolisen järven virtaus: pitoisuudet pysyivät samalla tasolla määritysten välillä eikä selvää pitoisuuden muutossyvyyttä havaittu.

Lumipeitteen ja kohvajään sulamisen jälkeen auringonsäteily voi läpäistä kirkkaan teräsjään ja lämmittää jäänalaista vesikerrosta. Sen lämpötilan ollessa alle veden maksimitiheyden lämpötilan auringonsäteilyn absorptio lisää veden tiheyttä aiheuttaen kevätkierron alkamisen vertikaalisen konvektion myötä. Sekoittuneen kerroksen syvyyden Pääjärven syvänteessä havaittiin riippuvan veden lämpötilajakaumasta syyskierron lopussa. Vertikaalisen konvektion lisäksi myös lateraalinen virtaus vaikutti jäänalaisen sekoittumiskerroksen syvyyteen. Järvien litoraali- ja sublitoraalialueiden lumi- ja jääpeite sulavat usein aiemmin kuin syvännealueet, ja mataluuden vuoksi ne usein myös lämpenevät ja sekoittuvat aiemmin. Lämpötilamittauksiin perustuen järven matalilla alueilla havaittiin kehittyvän advektiivinen virtaus kohti syvännealuetta, ja se vaikutti syvännealueen pohjaosien lämpötilajakaumaan.

Yleisesti on oletettu, että järvien kevättäyskierto alkaa jääpeitteen sulamisen jälkeen tuulen vaikutuksesta. Tässä seitsenvuotisessa tutkimuksessa Pääjärven (maksimisyvyys 85 m) havaittiin sekoittuvan kolmena vuonna pinnasta pohjaan syvännealueen ollessa vielä jääpeitteinen. Havainto jäänalaisesta täyskierrosta on harvinainen, ja yllättävää on nimenomaan ilmiön yleisyys. Jäänalainen kevätkierto oli todettavissa lämpötilamittausten ohella myös happipitoisuuden tasoittumisella koko vesipatsaassa.

Makean veden termodynaamisten ominaisuuksien sekä ilmakehän ja veden vuorovaikutusten vuoksi järviekosysteemien ilmastovasteen arviointi on haasteellista. Ilmastonmuutoksen vaikutuksia järviin on tutkittu pitkien aikasarjojen, kokeellisen tutkimuksen ja mallintamisen avulla. Avovesikaudella veden pintalämpötilan nousu voi johtaa myös alusvesikerroksen ja sedimentin lämpötilan nousuun suurissa järvissä tuulen vaikutuksesta. Syksyn ja alkutalven lämpeneminen viivästyttävät jääpeitteen tuloa, mikä voi johtaa veden jäähtymiseen. Jäähtymisen ja pidemmän avovesikauden seurauksena järvien happipitoisuus lisääntyy ja sedimentin ja sen yläpuolisen vesikerroksen lämpötilaero pienenee, mikä vaikuttaa talviajan virtauksiin. Jos jääpeite muodostuu lämpimän kesän jälkeen aikaisessa vaiheessa, sen vaikutus happitilanteen kehittymiseen ja jäänalaiseen hydrodynamiikkaan voi olla merkittävä. Kevään lämpeneminen aikaistaa jääpeitteen sulamista ja lyhentää aikaa, jonka vesi on eristyksissä kaasunvaihdolta ilmakehän kanssa. Omalta osaltaan myös jäänalainen kevätkierto vaikuttaa happipitoisuuden nousuun järvien syvänteissä, ja sen havaittiin olevan yleisempää syvänteen pohjanläheisen veden lämpötilan ollessa kylmempää. Rehevissä järvissä, joissa happipitoisuus talven aikana on laskenut alhaiseksi, jäänalainen kevätkierto voi johtaa vähähappisen veden sekoittumiseen koko vesipatsaaseen.

Ilmakehän lämpötilan nousu vaikuttaa ratkaisevasti talvikauden kehitykseen boreaalisissa järvissä, ja jääpeitteisen ajan lyheneminen on jo havaittavissa pitkistä aikasarjoista. Järvien lämpötilajakaumassa on myös talvisin paikallista ja ajallista vaihtelua, joiden vaikutusta järviekosysteemien toimintaan ei vielä tarkoin tunneta. Tulevaisuuden sopeutumiskeinojen selvittämiseksi ja vesistöjensuojelun tehostamiseksi tarvitaan lisätietoa myös jääpeitteisen ajan olosuhteista järvissä, mikä edellyttää monialaisen osaamisen ja tutkimuksen yhdistämistä.

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ORIGINAL PAPERS

I

THERMAL STRUCTURE OF AN ICE-COVERED, DEEP BOREAL LAKE (PÄÄJÄRVI, SOUTHERN FINLAND)

by

Merja Pulkkanen, Timo Huttula & Kalevi Salonen 2013

Manuscript

Thermal structure of an ice-covered deep boreal lake (Pääjärvi, southern Finland)

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Abstract

We investigated the under-ice thermal structure of a deep boreal Finnish lake, Lake Pääjärvi, during six winters from 2004/05 to 2009/10. Water temperature was measured continuously with temperature recorders from October to the end of April from the deepest location of the lake. The lake became isothermal during autumnal turnover at temperatures varying from 4.8 to 5.8 °C. After that the cooling continued and minimum near-bottom water temperatures were often reached before the complete formation of the ice cover. At that time, the mean temperature in the whole water column varied from 1.2 °C in the winter 2007/08 to 2.8 °C in the winter 2004/05. Although the under-ice water column was isolated from the mixing effects of wind, the thermal structure was not stagnant. The differences in under-ice water temperature between the surface and bottom layers were small (weak thermal stratification) enabling slow currents to exist. After reaching the minimum temperature, the increase in water temperature in the near-bottom layer was maximally 0.5 °C. Heat accumulation in the deepest part (> 50 m) of the water column was caused by advective currents generated by sediment heat flux. In mid-winter, the upper part of the lake water column was cooling due to the heat flux from water to ice. After the snow cover on lake ice melted, the surface water temperature started to increase due to the penetrating solar radiation, leading to the onset of vertical under-ice convection. Our study demonstrates that heat fluxes from sediment to water in the bottom and from water to ice at the surface in mid-winter as well as surface warming caused by absorption of solar radiation later in the course of winter are the main factors controlling the under-ice thermal structure of Lake Pääjärvi.

Key words: Advection, convection, ice cover, sediment heat flux, stratification, water temperature.

Introduction

Alternation of ice-free and ice-covered periods has a profound impact on the biology and biogeochemistry of boreal dimictic lakes (Baehr & DeGrandpre 2004). Physical forcings affecting the hydrodynamics of lakes differ dramatically between these two seasons. In summer, the thermal stratification of lakes restricts vertical mixing and the transport of substances between epi- and hypolimnion. In winter, with much weaker inverse stratification, vertical transport can be greatly reduced when ice cover provides isolation from mixing effects of wind (Ellis et al. 1991). In addition, the ice cover isolates lake water from the atmosphere reducing heat and gas exchange, and together with snow cover it attenuates solar radiation (Adams 1981).

Winter thermal conditions of lakes are determined by autumnal weather conditions and by lake characteristics (Hutchinson 1957). At the density maximum of fresh water, 3.98 °C, the expansion coefficient changes sign, which is the basis for the winter inverse thermal stratification in lakes (Farmer & Carmack 1981). In small and sheltered lakes ice cover develops soon after the water has cooled to 3.98 ^{o}C and the surface layer continues to cool. In large lakes, which are susceptible to wind, autumnal circulation can persist longer so that the temperature in the whole water column decreases well below 3.98 ^{o}C. After the formation of ice cover and in a case with no significant through-flow, the thermal structure of a lake in mid-winter is controlled by heat flux from the sediment to water and heat flux from water to the ice cover (Bengtsson 1996).

In fact, the hydrodynamics in winter are far from stagnant. It has long been recognized that there are slow water movements beneath the ice; for example, Birge et al. (1927) found water sinking due to the sediment heat flux. Nevertheless, only few direct measurements of under-ice currents have been made due to a lack of easy and efficient methods. Likens & Hasler (1962) used radioisotope technique to study the circulation pattern in Tub lake in North-America. Welch & Bergmann (1985) used dye experiments to show mid-winter water movements in an arctic lake. High-resolution mechanical devices have also been developed for under-ice measurements (Glinsky 1998). However, most evidence for slow water movements under ice has been collected with indirect methods, especially temperature measurements.

Mortimer (1941) observed slow currents under the ice of Esthwaite Water in the United Kingdom, and suggested that they were caused by heat released from the sediment to the overlying water. Mortimer & Mackereth (1958) found that the under-ice rise in the lake water temperature was accompanied by a decrease in oxygen concentration and rise in alkalinity and conductivity in ice-covered lakes in northern Sweden. In North-American ice-covered lakes, Stewart (1972) found variation and irregularities in lake isotherms depending mostly on the lake morphometry. Based on temperature profiles and direct current measurements of two Canadian lakes with no through-flow, Kenney (1996) concluded that the dominant physical process under ice is a lake-wide baroclinic water flow directed from the littoral zone to the deep parts of the lake. Both the penetration of solar radiation through the ice in spring and the heat flux from the bottom sediment could cause the water movement. Although snow is quite opaque, solar radiation can easily penetrate the clear congelation ice (black ice). Arst et al. (2008) reported that albedo for fresh snow is 0.85-0.94 and for Lake Pääjärvi congelation ice 0.29.

Climate change can alter the physical characteristics of a lake with complex influence on the lake heat content (e.g. Rempfer et al. 2010). In winter, the fate of ice cover formation (i.e. whether the cover is intermittent or continuous) will determine the response of a lake to atmospheric forcings (Peeters et al. 2002, Livingstone & Adrian 2009). As the water temperatures follow increasing air temperatures in the open water period (summer) and stratification is predicted to be more stable (Livingstone 2003), the length and conditions during the autumnal cooling period determine the thermal structure of the lake for the next winter and have an impact also on the following spring. Small and large lakes respond differently to the atmospheric forcings (Saloranta et al. 2009, Kirillin 2010). Future climate simulation results from Lake Pääjärvi suggest that warmer autumn air temperatures will delay freeze-over and affect ice thickness but will not change water temperatures markedly (Saloranta et al. 2009). Prolonged autumnal turnover and cooling period may actually slightly decrease water temperatures during winter in the future.

In this study, we investigated the thermal structure of a deep boreal lake during six winters from 2004/05 to 2009/10. We focused on the thermal changes in the surface and bottom water layers in the deepest location of the lake to characterize the under-ice water movements within the lake. Such detailed temperature measurements covering both the autumnal cooling as well as the ice-covered period provide improved understanding of these two neglected phases in the seasonal cycle of lakes.

Materials and methods

Lake Pääjärvi (61^{o}04′N, 25^{o}08′E) in southern Finland is a dimictic, meso-oligotrophic and mesohumic lake with water colour varying from 45 to 80 mg Pt L^{-1} annually (Fig.1). The surface area and total volume of the lake are 13.4 km^2 and 0.2 km^3, respectively. The mean and maximum depths of the lake are 14 m and 85 m, respectively, and the depth zone of >50 m is 3.4 % of the total water volume. The catchment area of Lake Pääjärvi is 212 km^2 and the mean water residence time is 3.3 years. Three rivers and two brooks drain into Lake Pääjärvi, accounting for 84 % of the total catchment area of the lake. Based on the discharge data for the river with the largest sub-catchment area, the River Mustajoki, and comparison of the sub-catchment areas of the other rivers and brooks to that of River Mustajoki, we estimated that the mean river inflow during autumn (September-November) 2003/09 was 4.7 % of the whole water volume of the lake. In the same period the mean outflow from Lake Pääjärvi via the River Teuronjoki was 6.4 % of the whole water volume of the lake. In winter (December-February) and in spring (March-May) 2004/10 the inflow accounted for 3.7 and 7.4 %, and the outflow accounted for 9.5 and 10.7 % of the whole lake volume, respectively (data from the Finnish Environment Institute, Hertta database).

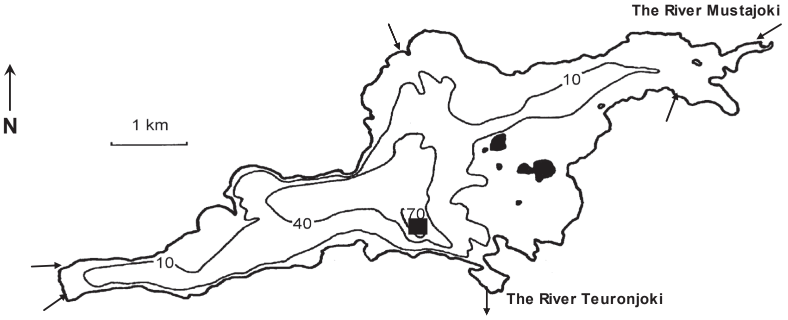

Figure 1. Bathymetric map of Lake Pääjärvi. The arrows show the main river inflows and outflow to the lake. The measurement station (in 2004-2010) at the deepest location is marked with a square.

With the exception of ice formation and thawing phases, ice and snow layer thicknesses were measured by the Finnish Environment Institute every ten days from the western bay of Lake Pääjärvi. Air temperature data and ice phenology data were obtained from Lammi Biological Station (University of Helsinki) adjacent to the lake. Wind speed data from Hämeenlinna weather station 40 kilometers south-west from Lake Pääjärvi were provided by the Finnish Meteorological Institute. Hourly data were available only for the years 2007/08-2009/10. Long-term lake water temperature data in winter (March or early April) were obtained from the Hertta database of the Finnish Environment Institute. Water temperature was continuously measured from the deepest location of the lake with Starmon mini –temperature recorders (Star-Oddi, Iceland; measuring accuracy ± 0.05 ^{o}C; average resolution 0.013 ^{o}C), which were attached to a rope between a float and a bottom weight. Recorders were placed at 1 m, 5 m and thereafter at 5 m intervals down to the depth of 75 m in a location with maximum depth of 78 m. The recorders were set to measure temperature at 30 min intervals from October to the end of April. Water densities were calculated according to Millero et al. (1980) and Millero & Poisson (1981). Isotherm graphics are based on linear interpolation produced with SigmaPlot 11.0 and long-term water temperature statistics with SPSS 20.0. Linear trend model was fitted to the long-term temperature data. Also partial autocorrelations with lag from 1 to 16 years were analysed but no significant correlations were found.

Results

In autumn the decrease in solar radiation leads to the cooling of lake water and eventually in the breakdown of summer stratification. In Lake Pääjärvi the autumnal turnover started with the cooling of the upper part of the water column and the mixed layer deepened progressively. We determined the beginning of full autumnal turnover based on changes in daily mean water column temperatures. The lake water column was considered to have overturned when the temperature difference between surface (in the depth of 1 m) and bottom (in the depth of 75 m) was close to zero (≤ - 0.07 °C) for the first time during autumn, and the standard deviation of the mean daily temperature of the water column was small (≤ 0.03). Lake Pääjärvi became isothermal at 4.76 – 5.84 °C during the study years (Table 1). After the mixed layer reached the lake bottom, the lake continued to cool until freeze-over. The duration of the period from the full autumnal turnover to the freeze-over varied from 27 days to 75 days and was shortest in the winter 2004/05 and longest in the winter 2006/07.

Table 1. Characteristics of the autumnal cooling period after turnover and of ice phenology in Lake Pääjärvi during winters 2004/05 – 2009/10. Autumnal turnover temperatures are mean water column temperatures (±SD) in the first day of isothermicity in the deepest location of the lake. The duration of the cooling period was calculated from the autumnal turnover to ice-on (ice cover phenology data: Lammi Biological Station, University of Helsinki). * = Long-term average in the region (Kuusisto 1994); ND = no data.

Winter	Turnover temperature (°C)	Autumnal turnover	Duration of cooling (d)	Ice-on	Ice-off	Ice cover duration (d)
1961-90*	-	-	-	30 Nov	5 May	156
2004/05	5.28 (± 0.02)	16 Nov	27	13 Dec	29 April	137
2005/06	5.84 (± 0.02)	21 Nov	31	22 Dec	4 May	133
2006/07	4.76 (± 0.02)	8 Nov	75	22 Jan	11 April	79
2007/08	ND	ND	ND	24 Jan	23 April	90
2008/09	5.53 (± 0.03)	18 Nov	46	03 Jan	26 April	113
2009/10	5.72 (± 0.03)	30 Oct	45	14 Dec	27 April	134

There was a high daily variation in air temperature before the freeze-over during the study years but as the air temperature decreased below zero, and when wind speed was low enough, the lake froze over (Fig. 2 and 3). Unfortunately hourly data of wind speed for the first three years were unavailable. In the winter 2007/08 the water temperature at 1 m depth was very low and constantly decreasing during one month before freezing (Fig. 3). Nevertheless Lake Pääjärvi remained unfrozen for a period of 1.5 weeks with air temperatures below zero. At that time there were frequent episodes of strong wind (5-10 m s^{-1}), preventing complete freeze-over and cooling the surface lake water close to 0 °C. The lake eventually froze over on 24th of January, after a short period with no wind. In 2008/09 the air temperature fluctuated above and below 0 °C during the last month before freezing of the lake, and the water temperature was decreasing constantly (Fig. 3). The lake froze over when air temperature decreased to -15 °C, and air temperature remained continuously below 0°C for 3-4 days and wind ceased. In 2009/10, the water temperature at 1 m depth remained at 4 °C and the air temperature was above 0 °C for most of the month preceding freeze-over of the lake (Fig. 3). At the onset of freezing, the air temperature decreased to -15 °C and a very calm period followed.

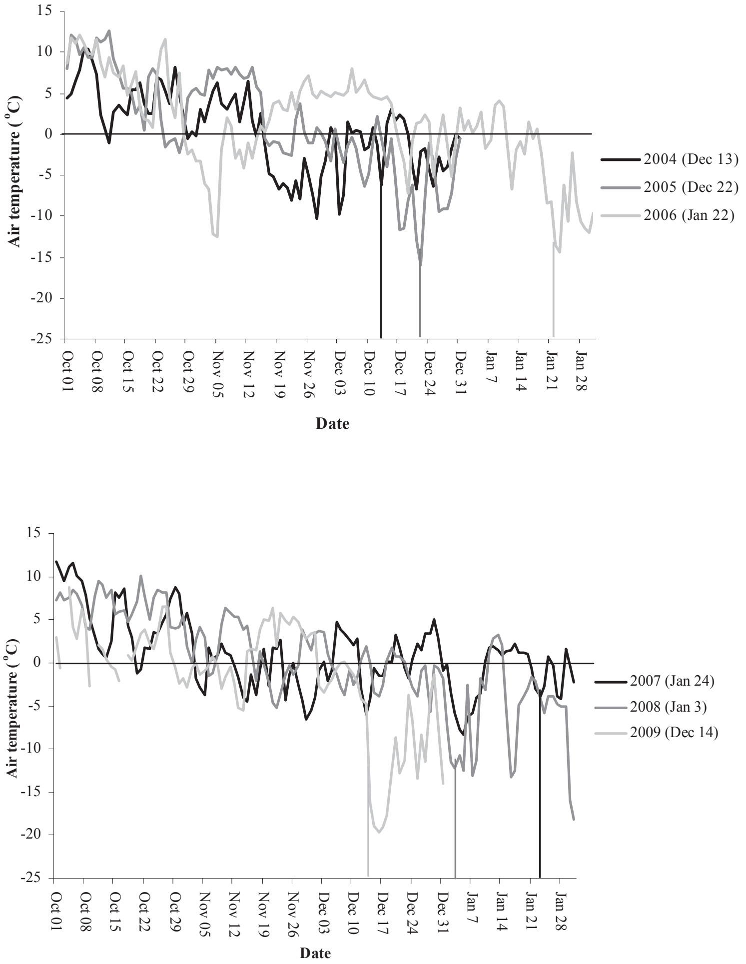

Figure 2. Daily mean air temperature (°C) in autumn/early winter during the study years. The date of ice-on in Lake Pääjärvi is indicated with a vertical line.

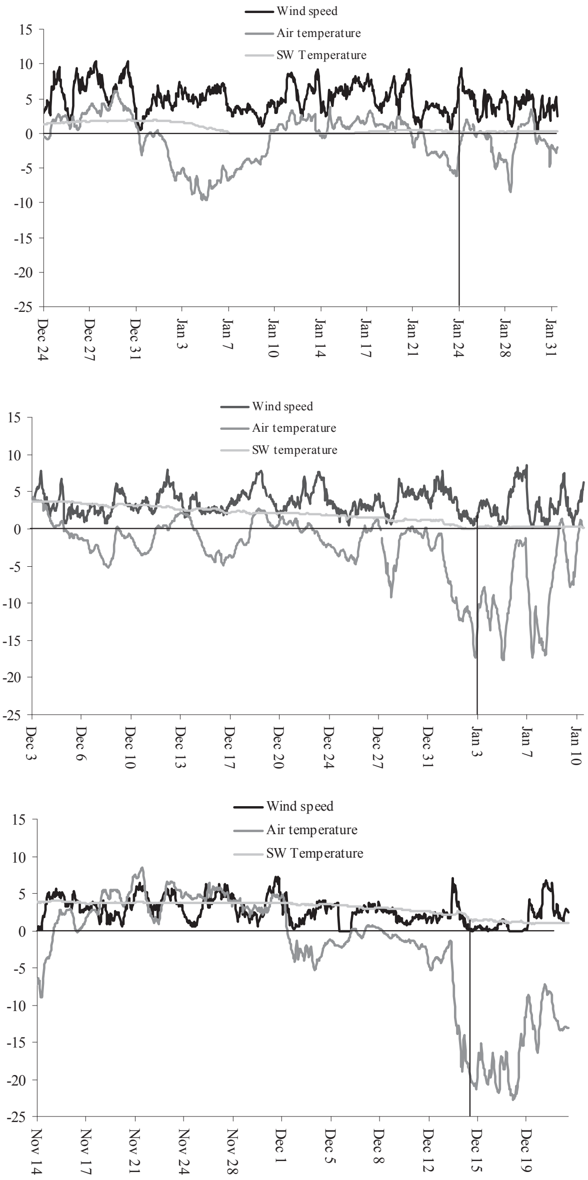

Figure 3. Hourly wind speed (m s^{-1}), air temperature (^{o}C) and surface water temperature (^{o}C) at 1 m depth during early winter 2007/08 (upper), 2008/09 (middle) and 2009/10 (lower panel). Date of ice-on is indicated with a vertical line.

In the winter 2006/07, Lake Pääjärvi froze over first on 9th January, then the ice melted and the lake froze over again on 24th January. Lake Pääjärvi froze in December in 2004, 2005 and 2010 (Table 1, Fig. 2). The ice-covered period was longest (137 days) in the winter 2004/05. The ice-covered period was shortest (79 days) in the winter 2006/07, when the first ice thickness measurement could not be made until the end of January and the last one was made already on 20th March with ice-off on 11th April.

In five of the six study years, the minimum temperature at the depth of 75 m was reached before or at the day of the complete formation of the ice cover (Table 2). In the winter 2004/05 the minimum temperature was observed more than two weeks before the freeze-over. After that the near-bottom water temperature started to increase, and in this year, the rate of increase was at first most rapid (Table 2). In the first five days of the warming period of the near-bottom water, the temperature increased almost 0.1 ^{o}C d^{-1}. In the winter 2009/10 the warming rate was also high (0.04 ^{o}C d^{-1}). The warming rate slowed down towards the end of the ice-covered period (one week before ice-off) and varied from 0.002 to 0.005 ^{o}C d^{-1} between the years. The absolute annual increase in the under-ice temperature at the depth of 75 m varied from 0.26 to 0.52 ^{o}C. The mean daily minimum water temperatures in the whole water column of Lake Pääjärvi varied from 1.20 ^{o}C (SD ± 0.66) to 2.76 ^{o}C (SD ± 0.07) on the day of minimum temperature at the depth of 75 m (Table 2). The mean water temperature of the whole water column was colder in those years when the freeze-over occurred in January than when it occurred in December.

Table 2. Evolution of temperature at the depth of 75 m in Lake Pääjärvi in the winters 2004/05 - 2009/10. Daily warming rates (from the minimum daily mean temperature at 75 m to one week before the ice out) are organised according to increasing mean temperature (±SD) of the whole water column on the day of minimum temperature at the depth of 75 m.

	2007/08	2006/07	2008/09	2009/10	2005/06	2004/05
Mean temperature (^{o}C)	1.20 (±0.66)	1.79 (±0.29)	1.91 (±0.88)	2.53 (±0.43)	2.59 (±0.65)	2.76 (±0.07)
Minimum temperature in 75 m	1.85	2.15	2.77	3.02	3.02	2.89
Warming rate (^{o}C d^{-1})						
5	0.010	0.003	0.006	0.038	0.006	0.096
10	0.009	0.006	0.006	0.022	0.007	0.039
20	0.008	0.006	0.005	0.013	0.006	0.021
40	0.006	0.005	0.004	0.008	0.005	0.010
50	0.006	0.005	0.003	0.007	0.005	0.008
60	0.005	0.005	0.003	0.006	0.004	0.007
80	0.005		0.003	0.005	0.003	0.006
100			0.003	0.004	0.003	0.005
120				0.004	0.002	0.004
140						0.004
Period length (d)	83	75	101	126	128	146
Temperature increase in 75 m (^{o}C)	0.39	0.33	0.26	0.43	0.31	0.52

The long-term (1965-2011) mean water column temperature of Lake Pääjärvi in March-April was 2.38 ^{o}C (SD ± 0.9 ^{o}C) indicating that it is a lake large enough to commonly cool well below the temperature of fresh water maximum density (Fig. 4a). There was no significant trend in the evolution of mean water temperature ($t = 1.289$, $p = 0.205$) (Fig. 4 a). The water temperature in the upper (1- 30 m) part of the water column was lowest in 1967 (mean 0.80 ^{o}C) and highest in 1991 (mean 2.56 ^{o}C). The water temperature in the lower (40-80 m) part of the water column was lowest in 2008 (mean 2.06 ^{o}C) and highest in 1999 (mean 3.96 ^{o}C). No significant trend in the evolution of surface water (1-20 m) or bottom water (60-80 m) temperature was found either, although the trend was slightly positive both for surface water ($t = 1.266$, $p = 0.213$) and bottom water ($t = 1.139$, $p = 0.261$; Fig. 4 b and c) as well as for the mean water temperature.

During mid-winter in most of our study years, the water temperature in the surface part (1-10 m) of the water column had more fluctuations and was still decreasing (Fig. 5). At the same time the water temperature was relatively constant in the middle part (30-40 m) of the water column, but increased clearly in the deepest part (> 50 m). In the winters 2004/05, 2005/06 and 2009/10 the water temperature varied from 0.00 ^{o}C (underside of ice) to roughly 3.25 ^{o}C in the near-bottom layer. The density difference between the surface and bottom under these conditions (temperature at the surface: 0.001 ^{o}C, salinity taken as the same in the whole water column; 0.05 PSU) was 0.16 kg m^{-3}. In the winter 2006/07 the water temperature varied from 0.00 to 2.25 ^{o}C and in the winter 2007/08 with the smallest range from 0.00 to 2.00 ^{o}C. The density difference between the surface and bottom parts of the water column was in this case 0.14 kg m^{-3}. In winter 2008/09 the range was 0.00 to 2.75 ^{o}C. The temperature gradients existed mostly above the middle part (30-40 m) of the water column. The surface water (1 m) temperature at the deepest location started to increase after the snow became absent from the ice cover (Fig. 5 and 6). In some years the temperature started to increase even before the snow melt in the western bay of Lake Pääjärvi. Towards the end of the winter, the upper part of the water column became isothermal at 1.25-3.0 ^{o}C in the layers down to the depth of 15-30 m (Fig. 5).

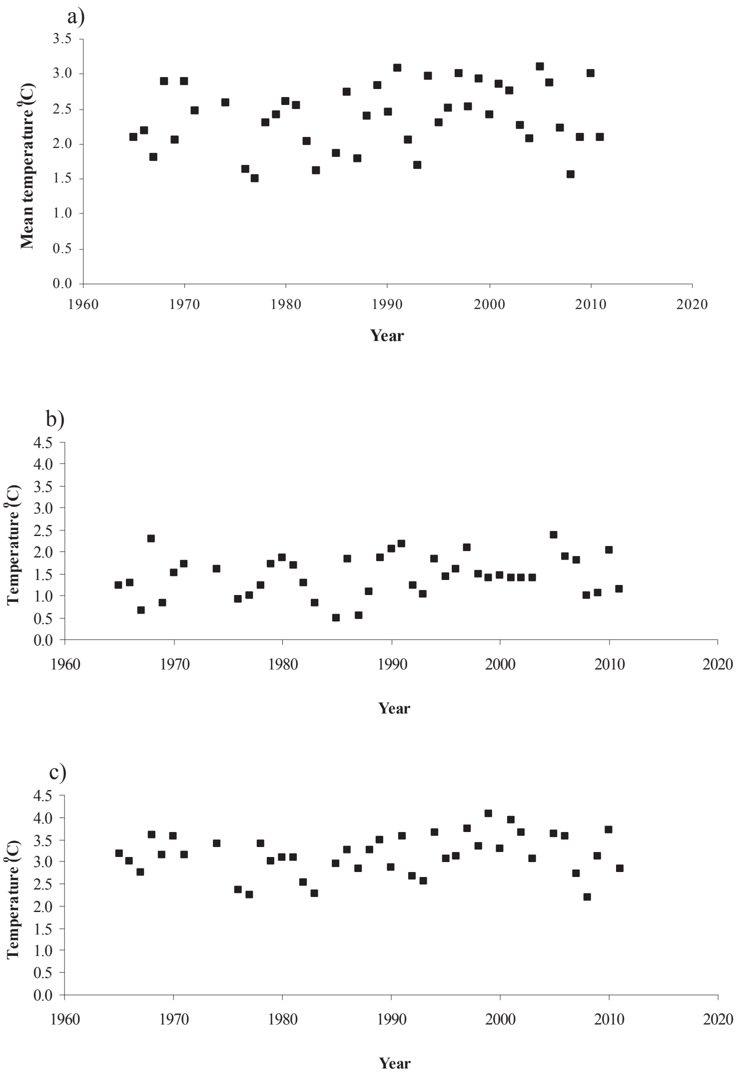

Figure 4. a) Mean water column temperature (°C), b) surface (depth of 1-20 m) water temperature (°C) and c) bottom (depth of 60-80 m) water temperature (°C) in March-April 1965-2011 in Lake Pääjärvi. Years 1972, 1973, 1975 and 1984 are excluded due to erroneous or missing values.

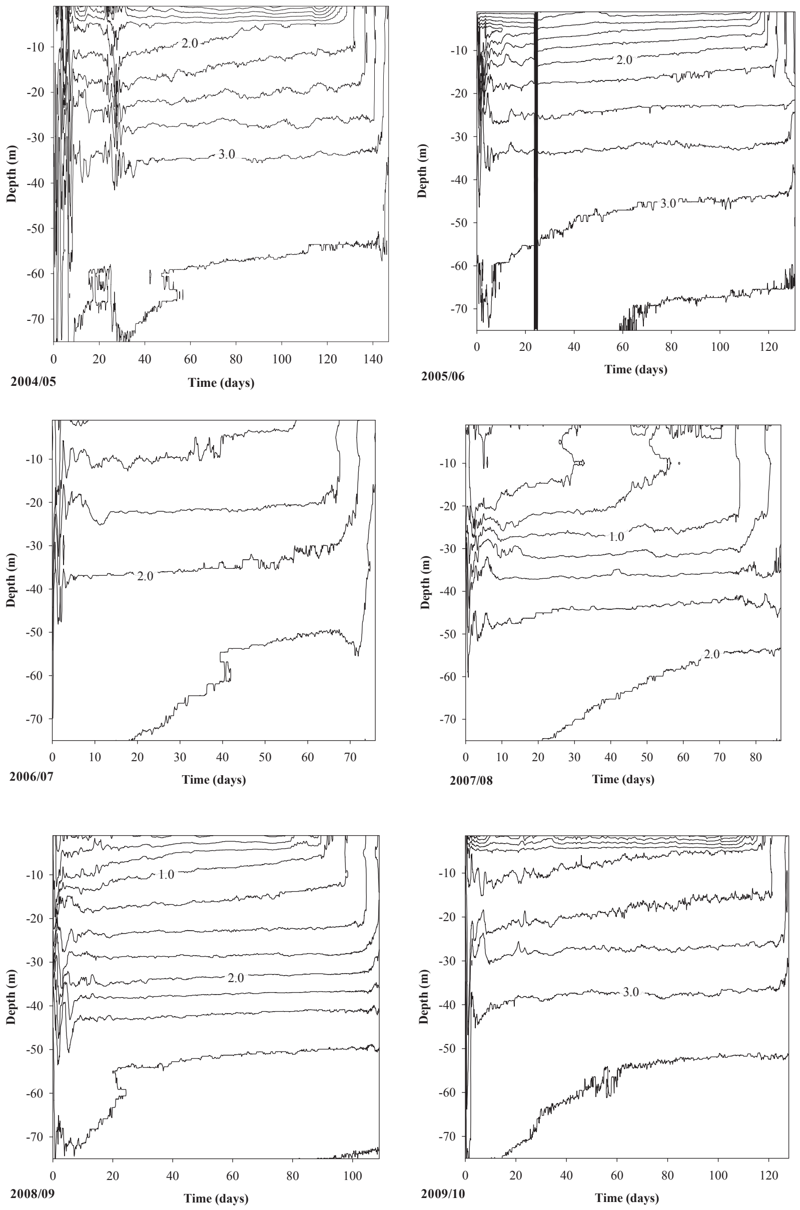

Figure 5. Evolution of water temperature (°C) in the deepest location of Lake Pääjärvi in the winter 2004/05 to the winter 2009/10 between the date of minimum temperature at the depth of 75 m and a week before ice-off. Linear interpolation with 0.25 °C spacing is based on a three hour (6 measurements) mean temperatures measured with the recorders.

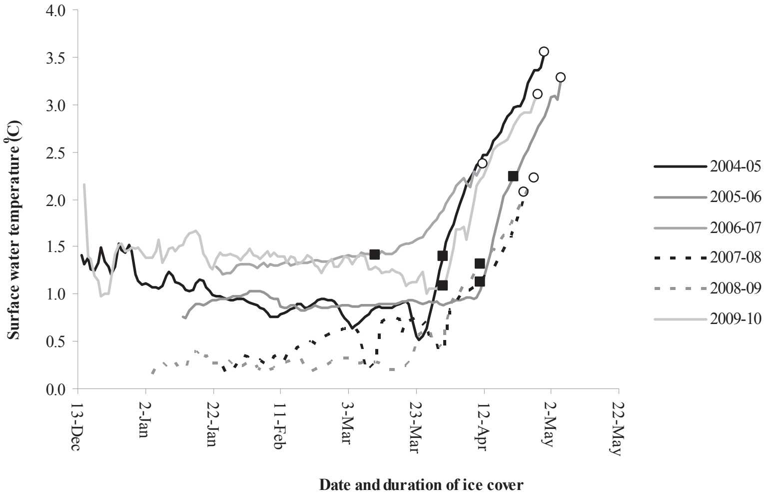

Figure 6. Evolution of surface water (1 m depth) temperature during the ice-covered period in Lake Pääjärvi. The date of the first observation with no snow on ice is indicated with a square, except in 2005/06, when the snow cover lasted until no observations could be made at all due to the weak ice (square indicating the first day with no observations). Ice-off is indicated with an open circle.

Discussion

The winter thermal characteristics of a lake are determined by autumnal weather conditions and lake area, depth and volume (Hutchinson 1957), with depth being the most important factor for lake freezing (Korhonen 2006). We found that after Lake Pääjärvi became isothermal at the onset of the autumnal turnover, even water layers near the bottom of such a deep lake continued to cool. The minimum temperature was usually reached before the complete formation of ice cover. According to the long-term data set and our results, the whole water column over the deepest location of Lake Pääjärvi commonly cooled well below the temperature of maximum density of fresh water, which has a profound impact on the winter hydrodynamics of the lake.

In winter, the temperature in the whole water column of Lake Pääjärvi remained higher in the years with early ice formation. This indicates that the autumnal weather conditions had a major role in determining the under-ice thermal structure. Our observations linked the onset of freezing most closely to the decrease in the air temperature, but wind episodes are clearly also important. Water temperature at the time of ice formation determines the weak under-ice stratification and therefore the density field (Hutchinson 1957). As climate change is increasing the air temperatures and the occurrence of extreme weather episodes (Jylhä et al. 2004), it is important to measure in detail air temperature, wind speed and wind direction measurements, preferably on the lake itself.

Lake responses to future atmospheric forcings depend on the stratification type and the lake morphometry. In small, sheltered and thermally stratified lakes the epilimnion can warm up very rapidly and the thermal stratification can be very strong, while in large lakes the hypolimnion can also become warmer due to efficient wind mixing (Saloranta et al. 2009). Although Lake Pääjärvi is relatively deep (mean depth 14 m) as compared to Finnish lakes in general (mean depth 7 m, the Finnish Environment Institute), the temperature in the deeper (> 40 m) part of the water column was commonly below 3.98 ^{o}C in winter, indicating effective mixing by wind and thermobaric convection during the autumnal cooling period. Still the minimum bottom temperature was reached before the complete formation of ice cover. No clear trend of warming or cooling of water can be found in the datasets of winter water temperatures covering more than four decades, but during our study, the ice-on occurred later than on average in the region during 1961-90 (Kuusisto 1994). This is in accordance with Magnuson et al. (2000), who reported a delay in freeze-over dates due to climate change. The slight positive trend in long-term March-April surface water temperatures in recent years may reflect the earlier onset of spring, and not necessarily warmer mid-winter temperatures in Lake Pääjärvi.

The near-bottom water layers become warmer due to sediment heat flux during winter. Under-ice temperatures are therefore higher in mid-winter than the onset temperature at the time of freeze-over in many lakes (Bengtsson & Svensson 1996). The warming rate in the near-bottom water layers at the deepest location did not seem to depend merely on the duration of the autumnal cooling period after full turnover or the initial under-ice water temperature. The weather conditions during the cooling period and the distribution of water temperature during a longer period may affect the warming rate. Over the course of winter, the warming slowed down as the temperature difference between the sediment and water became smaller. Nevertheless, we found a constant temperature increase in the lower (> 50m) part of the water column at the deepest location of Lake Pääjärvi. Because the water temperature in the whole lake was below 3.98 ^{o}C, sediment heat flux can generate advective density gradient currents flowing towards the deepest location, and accumulate heat in the deepest region of a lake. In addition to heat accumulation, advective currents can affect the distribution of dissolved oxygen in ice-covered lakes (Pulkkanen & Salonen 2012/II).

During mid-winter, the water temperature in Lake Pääjärvi cooled in the surface part (1-10 m depth) of the water column and remained quite stable in the middle part (30-40 m depth). In the winter 2003/04, Jakkila et al. (2009) found the heat flux from water to ice to be 5 W m^{-2}. The energy released from the cooling of surface water was absorbed in ice growth and, to a small extent, heat conduction through the ice. By the end of winter the snow cover on the lake ice melts and, due to the unique properties of solar radiation, the under-ice water temperature can increase (e.g. Farmer 1975, Matthews 1988). At that time water dynamics in the upper part of the water column can also change; when studying water-ice heat fluxes in Lake Pääjärvi, Shirazawa et al. (2006) and Jakkila et al. (2009) found that a mean horizontal current speed at the depth of 5 m increased from 0.5 – 1 cm s^{-1} to about 2 cm s^{-1} in the winter 2003/04 when solar radiation started to penetrate the ice cover. In our study, we found an increase in surface water temperature during all years well before ice-off, indicating that vertical convection can start under ice. In some years, the surface warming at the deepest location started before the snow cover had melted on the ice in the western bay of the lake. Adams (1981) emphasized that both snow and ice have an uneven distribution on lakes. Ice thickness can be greater at shore areas and snow also accumulates to the littoral regions of lakes due to wind action. This all affects the spatial thermal structure within a lake.

Sediment heat flux and solar radiation are the main sources of heat affecting the winter thermal characteristics of Lake Pääjärvi. Two other possible sources of heat, river inflow and groundwater input were negligible. The mean river inflow during December-February was only 3.7 % and in March-May 7.4 % of the whole water volume of the lake. Because the water colour remained the same in the whole water column of this mesohumic lake, groundwater input is presumably also negligible. Hence direct runoff and inflow of rivers can account for cooling of the lake in spring, but the cooling effect is restricted to a narrow water layer beneath the ice cover due to the inverse temperature distribution of the lake. The third observed heat flux, heat transfer from surface water to the ice, stabilizes the weak under-ice stratification. The density difference between the surface and bottom water was at most 0.16 kg m^{-3}. Sediment heat flux generates currents flowing to the deepest areas of lakes and solar radiation can induce the onset of spring turnover while the lake is still ice-covered and sealed from gas exchange with atmosphere. As climate change is predicted to delay freezing with a slight increase in early winter air temperatures, mean winter water temperatures in lakes susceptible to wind mixing are predicted to decrease (Magnuson et al. 2000, Saloranta et al. 2009). Yet higher air temperatures in spring lead to earlier ice-off and warmer water temperatures at the onset of the next growing season. Due to the small water density differences in the range of 1-3 ^{o}C, this may lead to differences in mixing patterns of a lake. More detailed knowledge of the thermodynamics in ice-covered lakes will provide a better basis to predict biogeochemical and biological changes in lakes associated with climate change.

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II

ACCUMULATION OF LOW-OXYGEN WATER IN DEEP WATERS OF ICE-COVERED LAKES COOLED BELOW 4 °C

by

Merja Pulkkanen & Kalevi Salonen 2013

Inland Waters 3: 15–24.

III

UNDER-ICE CIRCULATION IN A DEEP TEMPERATE LAKE

by

Merja Pulkkanen, Pauliina Salmi & Kalevi Salonen 2013

Manuscript

Under-ice circulation in a deep temperate lake

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Abstract

The amount of light available for photosynthesis increases abruptly in spring, while nutrient availability for algal growth is high. Consequently, spring is an important phase in the seasonal cycle of lake productivity with important ramifications for the ecosystem throughout the following growing season. It is traditionally assumed that the full turnover of water occurs only after ice-off, when the lake is exposed to wind. Here we show that a temperate lake, with winter water temperature less than 4 °C, undergoes spring turnover that starts days before ice-off. The turnover involves both vertical and horizontal (i.e. lateral) convective circulation. The under-ice turnover was strongest in those springs when water temperature was lower, conditions under which water density is most sensitive to temperature. Our measurements show that rather small inter-annual differences in water temperature, combined with stochastic weather variations in spring, can lead to quite different hydrodynamic conditions before the ice-off. The observed variation in the late winter mixing regime suggests a continuum of under-ice mixing regimes ranging from restricted vertical convection in small lakes to the thermal bar of large lakes, differences that may have far-reaching consequences for the biogeochemistry of lakes.

Key words: Convection, dissolved oxygen, ice cover, turnover, spring, water temperature.

1. Introduction

Although the convection caused by solar heating in ice-covered lakes has been recognized for a long time, the mechanisms and impacts on the lake ecosystem are still poorly known (e.g. Birge 1910, Farmer 1975, Matthews 1988, Jonas et al. 2003). During recent decades concern about climate change has increased the interest in winter limnology (Salonen et al. 2009), while the development of autonomous measurement devices has enabled more frequent data acquisition during the spring thaw period (Baehr & DeGrandpre 2002).

White snow cover on top of lake ice reflects most incident solar radiation (Adams 1981). After the snow disappears in spring, radiant heating through the ice warms the underlying water (Hutchinson 1957, Farmer 1975). In freshwater lakes having temperatures below 4°C, warming increases water density and causes thermodynamic instability leading to vertical convection (Bengtsson 1996, Mironov et al. 2002, Jonas et al. 2003). The solar heating process within a lake can vary both temporally and spatially; the snow and ice cover are unevenly distributed across a lake, with less thick cover in the pelagic region (Adams 1981). Thus in deep regions the heating can begin earlier, but it can be more pronounced in the littoral regions due to the smaller water depth to be heated (Stefanovic & Stefan 2002). The earlier warming of the littoral regions generates lateral, advective flow of water towards the deep regions of a lake (Stefanovic & Stefan 2002, Jakkila et al. 2009).

Due to the difficulties in measuring slow, under-ice currents during thaw, most of the information on water movements in ice-covered lakes is based on detailed temperature measurements (Farmer 1975, Mironov et al. 2002, Jonas et al. 2003). Under-ice convective mixing requires high solar radiation input, high water extinction coefficient, low initial water temperature, low density stratification and low vertical eddy diffusivity (Matthews & Heaney 1987). As vertical convection is predominantly local and has no net mass transport, whereas lateral convection involves relocation of water, nutrients and biota, as well as producing an earlier, deeper spring warming, these two classes of convection are likely to have different effects on the development of the spring phytoplankton maximum that is common in many temperate lakes (McKnight et al. 2000). Yet one of the most surprising consequences of under-ice convection is the occurrence of turnover, which has traditionally been assumed to take place only after ice-off and with wind forcing (Wetzel 2001).

Under-ice turnover can alter the concentrations of dissolved substances, most importantly dissolved oxygen (DO), while the lake is still ice-covered (Baehr & DeGrandpre 2004). In eutrophic lakes, mixing without addition of atmospheric oxygen may cause conditions leading to fish-kill (Greenbank 1945, LaPerriere 1981). Moreover, convection affects both the light climate and nutrient status of phytoplankton, which generally start intensive spring growth while still under the ice (Vehmaa & Salonen 2009).

We studied the under-ice thermal conditions of a deep boreal lake, (Lake Pääjärvi) to characterize the progress of spring convection at the deepest location of the lake during the end of the ice-covered period in 2004-2010. In addition, we investigated the evolution of dissolved oxygen (DO) concentration in 2004-2005 at the deepest location of the lake. With high-resolution temperature measurements and DO determinations, we observed an association of both vertical and lateral convection with the under-ice mixing depths.

2. Materials and methods

Lake Pääjärvi (61°04′N, 25°08′E) in Southern Finland is a dimictic, meso-oligotrophic and mesohumic lake with a maximum depth of 85 m (Fig. 1). The surface area of the fourth deepest lake in Finland is 13.4 km^2 and the total volume 0.2 km^3. The depth zone of >50 m is 3.4 % of the total volume. The catchment area of the lake is 212 km^2 and the residence time 3.3 years. Three rivers and two brooks drain into Lake Pääjärvi, accounting for 84 % of the total catchment area of the lake. Based on the discharge data of the river with largest sub-catchment area, the River Mustajoki, and the comparison of sub-catchment area of the other rivers and brooks to that of the River Mustajoki, we estimated that the mean river inflow during spring (March-May) 2004-10 was 7.4 % of the whole water volume of the lake. At the same period the mean outflow from Lake Pääjärvi via the River Teuronjoki was 10.7 % of the whole water volume of the lake (data from the Finnish Environment Institute, Hertta database).

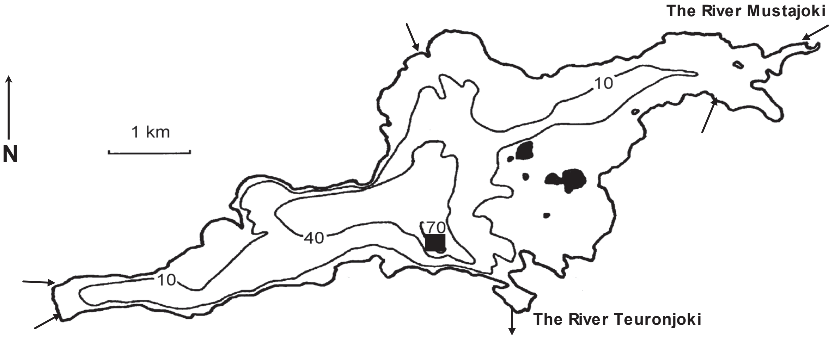

Figure 1. Bathymetric map of Lake Pääjärvi. The measurement location is marked with a square.

Water temperature was measured with Starmon Mini temperature recorders (Star-Oddi, Iceland; measuring accuracy ± 0.05 °C, average resolution 0.013 ˚C) at either one hour (2004) or half an hour (2005-2010) intervals annually from early March to May. The recorders in the water column were installed with 5 m (except at 1 m) depth increments down to the depth of 75 m in a location with maximum depth of 78 m. In 2004 dissolved oxygen samples were taken with a Limnos tube sampler from the same depths as the temperature recorders. When the ice was too weak to walk on, a hydrocopter (courtesy of Tvärminne Zoological Station, University of Helsinki), was used to access the sampling location.

The DO concentration in the samples was determined by a modified Winkler method with a Mettler Toledo DL53 Titrator (Mettler-Toledo International). In 2005 DO was measured with an Aanderaa Oxygen Optode 4175 sonde (Aanderaa, Norway; accuracy <8 µmol L^{-1} and resolution <1 µmol L^{-1}). The sonde was attached to a conductivity, depth and temperature meter (AML Micro-CTD, Canada). Water densities were calculated according to Millero et al. (1980) and Millero and Poisson (1981), for which conductivity (sensor accuracy 0.001 S m^{-1}, resolution 0.00015 S m^{-1}) was used to obtain salinity. Isotherm graphics are based on linear interpolation and were produced with MatLab version 7.0.1. Vertical temperature profiles were produced with Mapro-software (Hemsoft, Finland).

3 Results and discussion

During a 7-year campaign of high-resolution temperature measurements in Lake Pääjärvi the snow cover disappeared between late March and early April (Figs. 2, 3). During the last four weeks of ice in 2004-2010, the water temperature at a depth of 5 m increased by 0.8-1.6^{o}C reaching 2.3-3.5^{o}C at ice-off (Fig. 2). Owing to inverse thermal stratification (warmest at the bottom) the temperature at the depth of 75 m was 2.2-3.5˚C and increased by 0.2-0.5^{o}C. As the temperature throughout the water column remained well below 4^{o}C, warming at the surface resulted in convective mixing, which progressively penetrated deeper. The mean temperature of the convective layer at the time of ice-off varied quite widely between the years (2.3-3.5^{o}C) and showed a significant correlation ($r = 0.75$, $p = 0.05$) with temperature at 75 m before the impact of convection. Thus the heat content of the water mass before the beginning of spring solar heating affects the under-ice temperature at ice-off.

In the winter with the highest deep water temperature before convection (3.5^{o}C in 2010) the convective layer was approximately 40 m deep at the time of ice-off (Figs. 2, 3). In two other winters having deep water temperature greater than 3^{o}C, convection reached depths of 50-60 m. In contrast, the three years having the coldest bottom water (2.2-2.7^{o}C in 2004, 2007 and 2008) showed convective mixing extending down to the bottom 2-8 days before ice-off. Hence, the deep water temperature, or strength of the density stratification, affects the depth of under-ice convection. These results provide a rough empirical relationship between the mixing depth in Lake Pääjärvi and the mid-winter deep water temperature (Fig. 2, summary panel).

We note that heat flux from the sediment increased the deep water temperature through winter by only 0.2-0.5^{o}C, leaving the water temperature reached during the previous autumnal turnover as a major factor determining the depth of under-ice spring convection. Another factor of importance here is the temperature-dependence of the thermal expansion coefficient (which increases with decreasing temperature below 4˚C, so that a temperature change of 0.5˚C changes water density approximately three times more at 2˚C than at 3˚C): small differences in temperature may lead to marked changes in circulation, with more vigorous convection and, conversely, more stable density stratification, at lower temperatures.

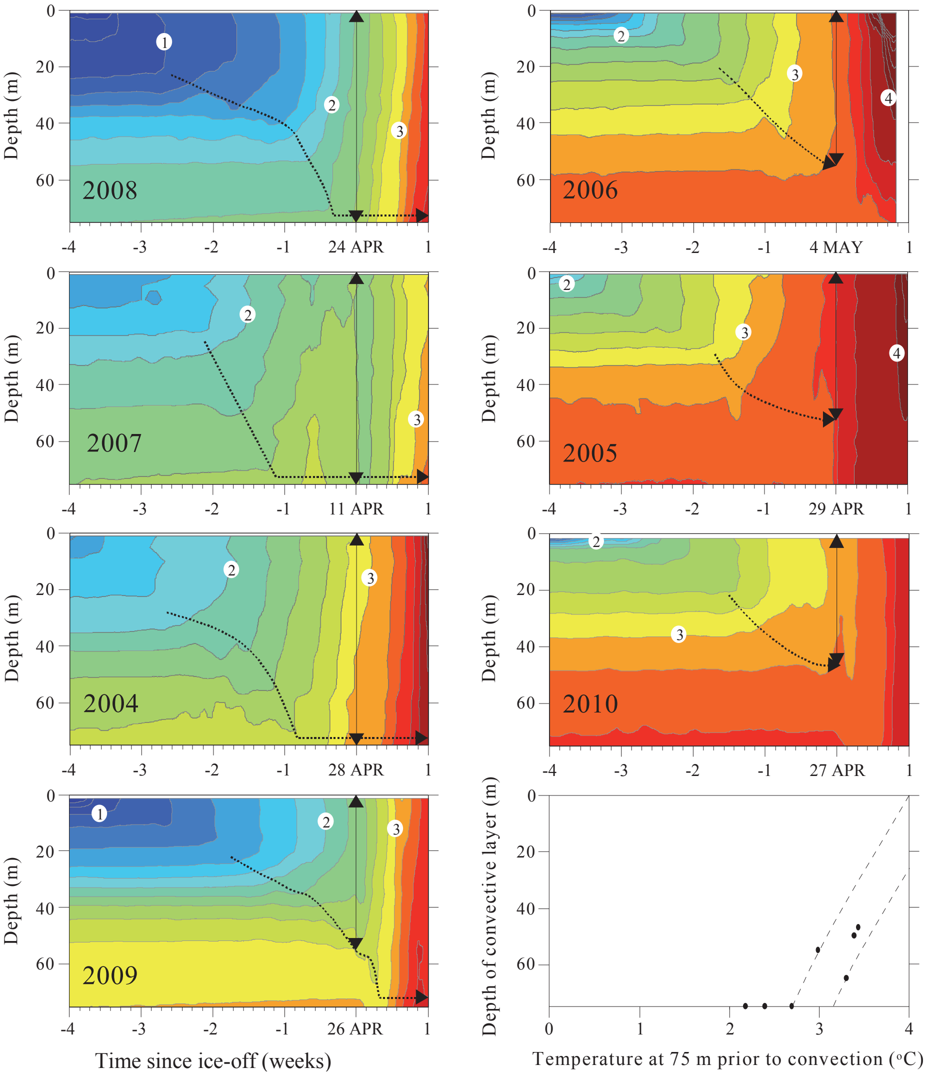

Figure 2. Development of water temperature (°C) and convective mixing during four weeks before and one week after the ice-off (date given at time zero) in the years 2004-2010 in the deepest location of Lake Pääjärvi. The isotherm panels with 0.2°C intervals of 24 h moving averages are arranged in the order of increasing water temperature at 75 m one month before the ice-off. Vertical arrows - Depth of convection at the end of ice cover; Dotted arrows - The evolution of the penetration of lateral convection (for clarity, after reaching 75 m depth, the arrows are drawn with slight upward offset). The diagram at lower right summarizes the dependence of the depth of convective mixing (at ice-off) on the temperature of the deepest water layers (before it was affected by convection); the left broken line is drawn through the theoretical maximum temperature of deep water and the highest temperature point of complete turnover; the right broken line is drawn in parallel to the left line through the extreme right hand point.

The measurements also show that vertical convection was not the only mechanism for water transport between upper and lower layers in the lake. When vertical convection reached roughly 25 m 6-10 days before the ice-off, the deepest part of the convective region developed a temperature anomaly up to 0.3°C higher than the upper, more uniform, region of convection (Figs. 2, 3). Along with the deepening of the convective layer, this positive temperature anomaly moved downwards and, in 2004, 2007 and 2008, it reached the bottom in the deepest part of the lake before the ice-off. Strikingly and especially in 2007, the deepest part of the lake warmed most intensively due to a deep warming event 5-7 days before ice-off.

The greater warming of deep layers compared with the bulk of the convecting layer is explained by horizontal (i.e. lateral) advective circulation. The most intense heating occurs in shallow water, where the solar radiation is absorbed and mixed through a smaller water volume (Stefanovic & Stefan 2002). Once the convective mixed layer is deep enough to reach the bottom in shallow regions, the warmer and more dense water flows from the littoral areas towards the deepest part of the lake (Jakkila et al. 2009). Under the spring ice the bathymetric convection does not always deliver water to the bottom; it instead delivers progressively denser water to the base of the vertically-mixed layer, where it can spread horizontally across the lake as an intruding layer (Ellis et al. 1991). Near the end of the ice-covered period the lateral convection is greatly emphasized by the disappearance of ice in shallow water and the associated absence of latent heat loss in the melting of ice.

In 2004 and 2005, the vertical concentrations of DO in Lake Pääjärvi changed in the same way as temperature already before the ice-off. In April 2004, the DO concentration during two weeks before ice-off was 11.5-12 mg L^{-1} down to the depth of 50 m and decreased then towards the bottom. The observed minimum DO concentration at 75 m depth was 6.7 mg L^{-1} on 20th April. As the mixing was extending to the bottom of the lake, DO concentration also increased to 11.5 mg L^{-1} on 25th April and became uniform (mean 11.8 mg L^{-1}, SD ±0.04) in the whole water column two days before ice-off (Fig. 4a). In April 2005, the initial DO concentration was already decreasing from the depth of 30 m downwards, DO was 10.6 mg L^{-1} (SD ±0.25) in the upper part (1-30 m) of the water column and decreased to 4.9 mg L^{-1} (SD ±1.20) in the lower part (65-75 m) of the water column (Fig 4b). During the end of April the DO concentration increased at 30-60 m depth, but near the bottom it was still low two days before ice-off, indicating that convection did not reach the bottom.

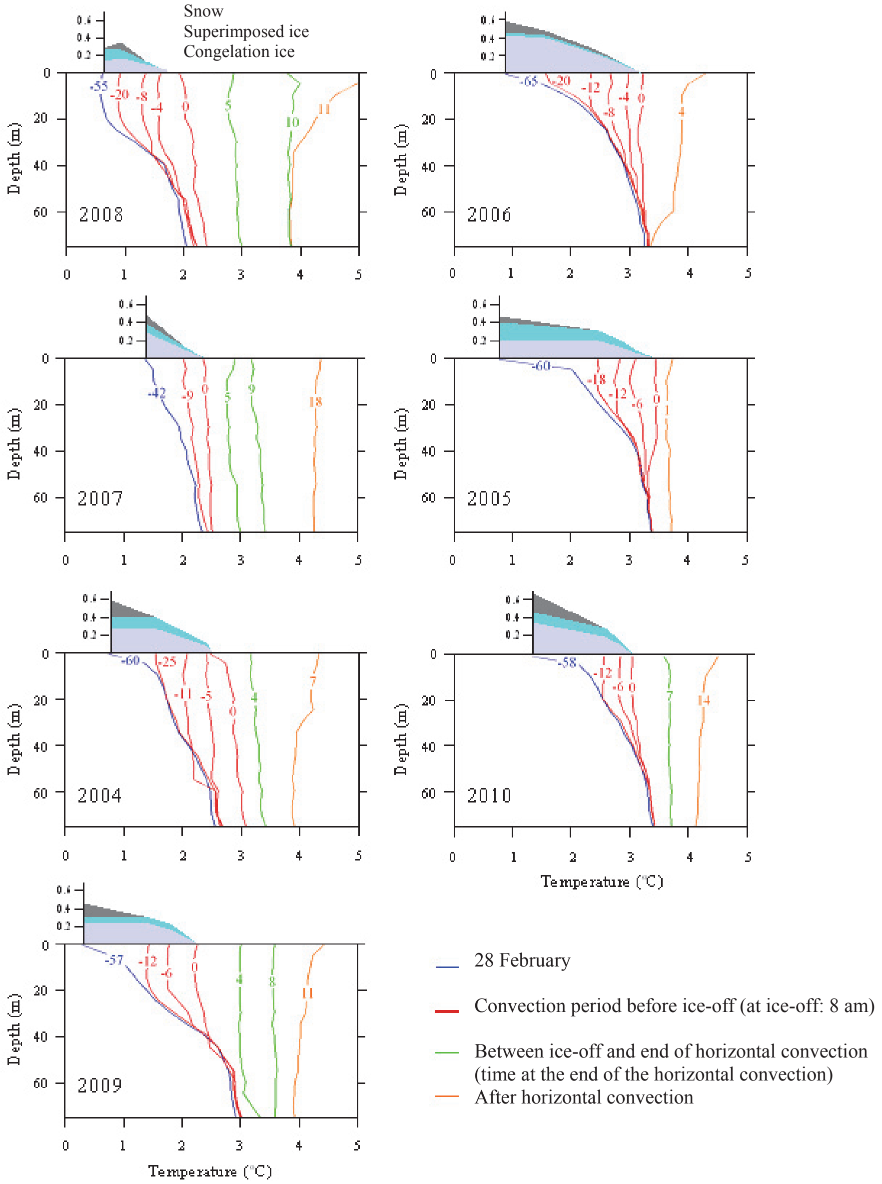

Figure 3. Evolution of water temperature in Lake Pääjärvi between four weeks before and one week after the ice-off. Vertical profiles are based on measurements taken at noon (exceptions are indicated on the legend). Depths of snow and ice layers are shown above the panels with times fixed to the upper ends of each graph. Numbers on profiles indicate days before/after ice-off.

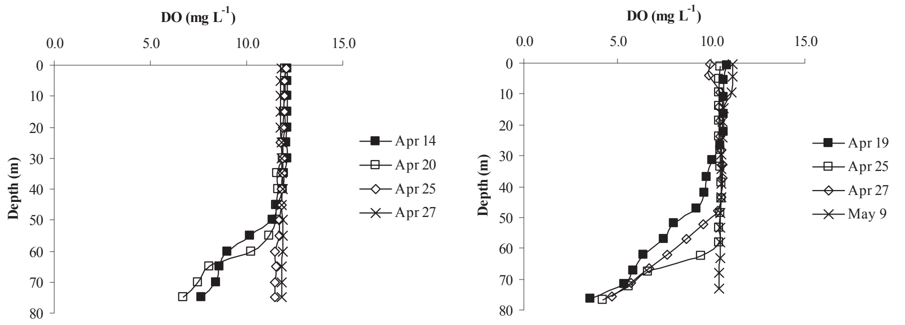

Figure 4. Evolution of DO concentration (mg L^{-1}) in Lake Pääjärvi in April 2004 (left panel; ice-off 28th April) and 2005 (right panel; ice-off 29th April).

In 2005 and 2010, the complete turnover of the water column followed almost immediately after the ice-off, while in 2009 and 2010 the complete turnover occurred 2 to 3 days after ice-off. In contrast, in 2004 and 2007-2008 lateral convection continued in the open water at temperatures below 4°C. Although the conditions approached the development of a thermal bar (e.g. Holland & Kay 2003), this phenomenon was not observed during the study.

The data are not sufficient to tell in detail how the water temperature reached by mixing in preceding autumns will influence the relative strengths of vertical and lateral convection at the deepest location in Lake Pääjärvi. However, the simple concepts discussed here, supported by observations from Lake Päijänne (a basin roughly 10 times larger than Lake Pääjärvi and sometimes reaching temperatures close to 1°C; Kiili et al. 2009), indicate that low winter water temperatures favour lateral convective circulation over purely vertical convective mixing.

Both the temperature and DO data show that Lake Pääjärvi, the fourth deepest lake in Finland, undergoes frequent under-ice turnover. We therefore postulate that this phenomenon is likely to be common in lakes where winter temperatures are less than 4 °C. Still lower water temperatures give larger thermal expansion coefficients and therefore intensify convection on surface heat input. Hence under-ice turnover in spring is more likely in geographic localities favouring very low water temperatures, although to our knowledge it has previously been reported from only few lakes; e.g. in subarctic lake, Lake Harding, Alaska (LaPerriere 1981) and in mesotrophic Lake Placid, Montana (Baehr & DeGrandpre 2004), lakes with maximum depths of 42 m and 27 m, respectively.

In more eutrophic lakes, mixing by vertical and lateral convection can be restricted by accumulation of dissolved electrolytes in deep water during winter. However, Lake Pääjärvi is a deep and oligotrophic lake, where deep water oxygen is never depleted, and we detected under-ice turnover to occur in three out of seven years. In shallower oligotrophic lakes under-ice turnover may be even more frequent.

Under-ice mixing patterns affect the water exchange between surface and bottom waters and also between different locations of Lake Pääjärvi, with possible impacts on the biogeochemical processes and species composition as well as species distribution within a lake (Vehmaa & Salonen 2009). More detailed knowledge about the under-ice events and the factors affecting them is needed to assess the ecological consequences for temperate, ice-covered lakes of a changing climate.

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IV

SPATIAL DEVELOPMENT OF UNDER-ICE MIXING IN A DEEP BOREAL LAKE

by

Merja Pulkkanen & Kalevi Salonen 2013

Manuscript

Spatial development of under-ice mixing in a deep boreal lake

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Abstract

We studied the evolution of water temperature and the progress of under-ice spring isothermal mixing in terms of mean water column temperature in deep, boreal Lake Pääjärvi, in both a cold year (2004) and a warm year (2006). The water temperature measurement locations extended from the sublittoral area (bottom depth of 10 m) towards the deep (75 m) central region of the lake. During the last four weeks of the ice cover, the mean temperature of the water column in the deepest location increased by 0.9 ^{o}C in 2004 and by 0.6 ^{o}C in 2006. The period of isothermal mixing began in the sublittoral regions of the lake three to two weeks before ice-off. This under-ice mixing was associated with both vertical convection in the surface layer and lateral, advective flow of water in the bottom layer of the lake. Both flows were triggered by solar radiation penetrating the ice cover. In 2004 the mean temperature of the water column at the deepest location was 2.1 ^{o}C at the beginning of the study period. The turnover of the water column occurred before ice-off at 2.6 ^{o}C. In 2006, the mean temperature of the water column was higher (2.7 ^{o}C) at the beginning of the study period with a stronger vertical temperature gradient. There was no clear isothermal turnover phase at the deepest location, and the lake started to stratify soon after ice-off. More detailed knowledge about under-ice mixing in spring and the factors affecting it are important for assessing the responses of lakes to future changes.

Key words: Advection, convection, spring turnover, water temperature.

Introduction

Spring and autumnal turnover periods are particularly significant phases in the seasonal cycle of lake ecosystems (Baehr & DeGrandpre 2002). When dimictic boreal lakes are thermally stratified in summer, dissolved substances are unevenly distributed in the water column and gas exchange between hypo- and epilimnion is restricted. In winter there is only a weak thermal stratification within the water column, but gas exchange between water and atmosphere is prevented by ice cover (Adams 1981). During the spring and autumn isothermal mixing phases, the concentrations of dissolved substances become uniform through the water column. Gases are then emitted to the atmosphere and dissolved to water more effectively. The spring isothermal phase is often shorter than the autumnal phase because after the ice cover has melted, lakes stratify rapidly due to absorption of both radiative and thermal energy.

Ice and snow cover are usually unevenly distributed in a lake (Adams 1981). Shallow regions close to the shore freeze over earlier than the central region of the lake, but as snow is accumulated on the shores by wind and acts as an insulator, the ice cover thickness can even out over the course of winter (Bengtsson 1986). After the melting of snow cover in spring, solar radiation penetrates the lake ice resulting in both melting of the ice and warming of the underlying water (Jakkila et al. 2009). There is a large spatial and temporal variability in the optical properties of boreal lake snow and ice cover components (Arst et al. 2008), affecting the timing and intensity of lake water heat absorption. In autumn, the water in large lakes can cool below 3.98 ^{o}C, the temperature of maximum density of fresh water. Therefore the warming of water by absorption of solar radiation increases its density and causes a convective current directed downwards in the water column (Matthews & Heaney 1987). The mechanism of convection induced by solar heating have been studied in detail by Farmer (1975), Mironov et al. (2002) and Jonas et al. (2003).

We studied the evolution of water temperature and mixing in terms of mean temperature of the water column in deep, boreal Lake Pääjärvi (southern Finland) during the last four weeks of the ice-covered period in both a cold year (2004) and a warm year (2006). The impact of preceding autumnal conditions on the water temperature was still apparent in the beginning of our study period, and the focus of this work was to investigate the progress of spring isothermal mixing during two springs differing in the vertical distribution of water temperature. Based on detailed measurements with temperature recorders, we followed the development of under-ice mixing along a measurement transect from the sublittoral zone in the 10 m depth region towards the deep central region (depth of 75 m) of the lake to characterize the factors affecting the under-ice mixing depth in a deep lake. We observed high spatial heterogeneity in lake temperature in under-ice conditions, which has a profound effect on lake biogeochemical and biological functions driven by hydrodynamics.

Materials and methods

Lake Pääjärvi is a mesohumic and dimictic lake with a surface area of 13.4 km^2 and maximum depth of 85 m (Fig. 1). It is the fourth deepest lake in Finland, and the mean depth of the lake (14 m) is higher than that of Finnish lakes in general (7 m, Finnish Environment Institute). The retention time of the lake is 3.3 years. Five rivers or brooks drain into the Lake Pääjärvi (indicated in Fig. 1). During March-May 2004 and 2006, the mean daily discharges of the largest inflow river, the River Mustajoki, and of the outflowing River Teuronjoki were 0.80 (SD ± 1.02) and 2.48 (SD ± 1.46) m^3 s^{-1}, respectively.

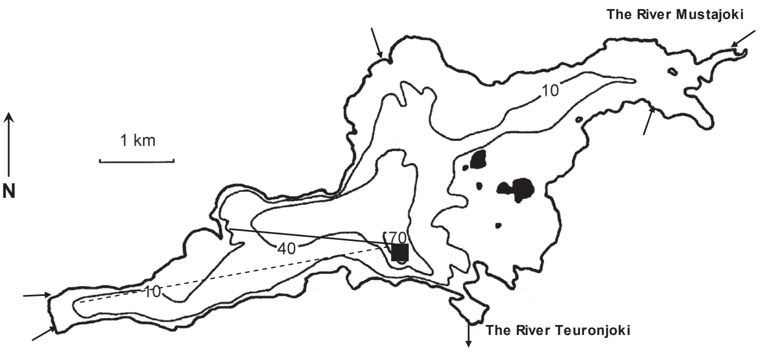

Figure 1. Bathymetric map of Lake Pääjärvi and the locations of measurement transects in 2004 (solid line) and 2006 (dashed line). The measurement station at the deepest location is marked with a square.

In 2004 and 2006, water temperature during the last four weeks of ice cover was measured from the deepest location of Lake Pääjärvi with Starmon Mini temperature recorders (Star-Oddi, Iceland; accuracy ± 0.05 °C, average resolution 0.013 ˚C) at one hour (2004) or half an hour (2006) intervals. The recorders in the water column were installed at 5 m (except at 1 m) depth increments down to the depth of 75 m in a location with maximum depth of 78 m (2004) or 78.6 m (2006). In addition, temperature recorders were installed at separate positions with bottom depths of 10 m, 20 m and 40 m (only in 2004). The uppermost recorder at each location was situated at a depth of 1 m (surface). The positions of the lowest recorders were between 0.4 – 0.7 m above the sediment. These locations formed a measurement transect from the north-western (in 2004) or western (in 2006) sublittoral zone to the deepest location of the lake (Figs. 1 and 2). The vertical depth increments of the recorders were similar to the increments at the deepest location.

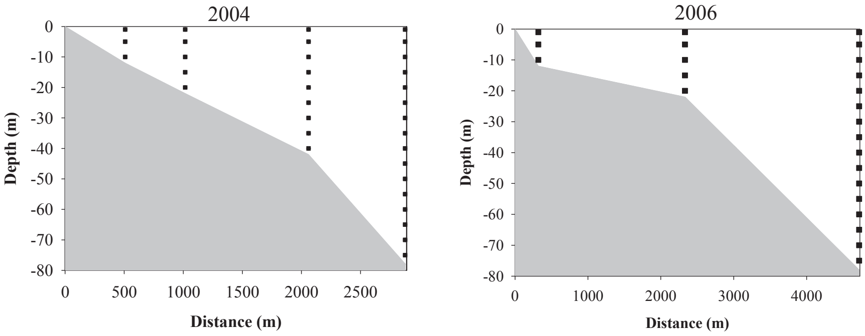

Figure 2. The distances between measurement locations and detailed positions of temperature recorders in the water column in 2004 and 2006 in Lake Pääjärvi.

Our intensive study period started on 31st March and ended on 28th April in 2004 and continued in 2006 from 6th April to 4th May. Temperature recorder data were used to calculate daily mean temperatures of the water column, daily mean surface water temperatures, and bottom water temperatures. Evolution of daily mean water temperature in the north-western and western measurement transects was described by the temperature field interpolated linearly between the measurement locations. Isotherm graphics were made with MatLab (MathWorks, R2012a). Daily mean temperatures were the mean of 24 (in 2004) or 48 (in 2006) measurements. Further, we assessed the water mixing based on changes in temperature; when the daily mean temperature of the water column became isothermal with a first small standard deviation ($SD \leq 0.06$) associated with a small variation (commonly slight decrease due to the reach of colder water above) in the bottom water temperature, the water column in the location was considered to overturn.

Hourly air temperature data were obtained from Lammi Biological Station, University of Helsinki, nearby Lake Pääjärvi. For the last four weeks of ice cover, degree-day values (W) were calculated as:

$$W = \Sigma (T_d - 5), \qquad (1)$$

including all days with $T_d > 5$, where T_d is the daily mean air temperature.

Daily global radiation data were obtained from the observatory of Jokioinen, Finnish Meteorological Institute, situated 100 km south-west from Lake Pääjärvi. Winter water colour and conductivity data from the deepest location of the lake were obtained from the Hertta database of the Finnish Environment Institute. Ice and snow cover thicknesses were measured by the Finnish Environment Institute from the western bay of Lake Pääjärvi every ten days.

Results

The evolution of lake water temperature during thaw is strongly affected by the ice, snow and weather conditions. In winter 2003/04 Lake Pääjärvi froze over on 21st Dec 2003 and in 2005/06 on 22nd Dec 2005. The ice cover duration was almost as long in both years (129 d in 2004 and 133 d in 2006). The last snow and ice observations in both years were made on 10th April, three weeks before the ice-off in 2004 and four weeks before in 2006 (Table 1). The study period in 2004 began with changes in the superimposed ice layer, which consisted of opaque snow ice and frozen rainfall or melt water. The snow cover was absent during the two last observation dates. On the last ice observation day of 2006, only the layer of snow had become thinner, but there was still snow on ice and the congelation ice cover was almost twice as thick as in 2004. The superimposed ice cover, with higher albedo than the congelation ice, was slightly thicker in 2004.

The incident global radiation was strong on a weekly basis throughout the study period in 2004, with a mean of 188.3 W m^{-2} (Fig. 3). During the last two weeks of ice cover in 2006, the global radiation was higher than in 2004 even though the first two weeks of the study period were cloudy and radiation was low. In terms of air temperature, the study period was warmer in 2006; during the study period, the degree day sum of air temperature (^{o}C) was 16.3 degree days in 2004 (31st March-28th April) and 38.0 degree days in 2006 (6th April- 4th May). Water colour affects solar radiation penetration into the water column. In winter 2004 the lake surface water colour at the deepest location of Lake Pääjärvi was 45 mg Pt l^{-1}. In winter 2006 the surface water colour of 70 mg Pt l^{-1} was clearly higher.

Table 1. Ice and snow cover thickness at Lake Pääjärvi on 30th March and 10th April, 2004 and 2006 (data from the Finnish Environment Institute).

	Congelation ice (cm)		**Superimposed ice (cm)**		**Snow (cm)**	
Date	2004	2006	2004	2006	2004	2006
30 March	26	48	16	5	0	22
10 April	25	47	9	4	0	6

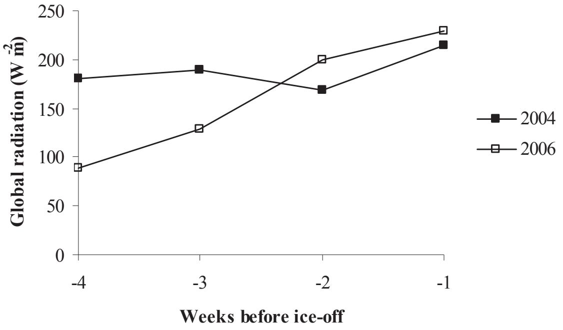

Figure 3. Weekly mean global radiation (W m^{-2}) during the last four weeks of the ice cover at Lake Pääjärvi.

The differences in weather and ice conditions between the study years affected the thawing process and vertical temperature profiles in Lake Pääjärvi. The mean temperature of the whole water column at the deepest location of Lake Pääjärvi at the beginning of the study period was 2.1 °C in 2004 and 2.7 °C in 2006 (Table 2). During the last four weeks of the ice cover, the daily mean water column temperature increased by 0.9 °C and 0.6 °C and the surface water temperature by 1.5 °C and 2.3 °C in 2004 and 2006, respectively. The major difference between the years was that in 2004, the bottom water temperature increased by 0.4 °C, but in 2006, the bottom water temperature remained almost the same during the last four weeks of the ice cover. Further, the surface water under the ice cover in 2006 was colder (1.0 °C in 2006 and 1.4 °C in 2004) at the beginning of the study period indicating a stronger temperature gradient within the water column, but the surface water warmed more rapidly in 2006 than in 2004. Snow and ice cover melted first from the shallow regions of the lake. In the shallow regions the same amount of solar radiation warms a smaller water volume than over the deepest location, so the shallow regions warm earlier. In 2004, the lake water column at the 10-m location became isothermal on 5th April at 1.7 °C (±0.02) and at the 20-m location on 7th April at 1.8 °C (±0.03) (Fig. 4), when the lake ice cover still extended to the shore. After the isothermal mixing of the water column in these locations, the bottom water temperatures were slightly (mean 0.1 °C) higher than the surface water temperatures during the three last weeks of ice cover. This indicates that, in addition to the vertical convection at the measurement locations, lateral, advective water flow along the bottom slope from the shallow regions to the deeper parts also occurred during the study period. The lake water column at the 40-m location became isothermal on 19th April at 2.2 °C (±0.04), eight days before the complete ice-off. At that location, the temperature difference between the bottom and surface was 0.2 °C a week before the ice-off. Due to the warming of water in shallow regions, warm advective flow was generated.

Table 2. Daily mean temperatures of the water column, and daily mean surface and bottom water temperatures at the deepest location of Lake Pääjärvi during the last four weeks of ice cover and at ice-off in 2004 and 2006 (± SD).

Day before ice-off	**Water column temperature (°C)**		**Surface water temperature (°C)**		**Bottom water temperature (°C)**	
	2004	2006	2004	2006	2004	2006
28	2.1 ± 0.44	2.7 ± 0.68	1.4 ± 0.06	1.0 ± 0.01	2.7 ± 0.01	3.3 ± 0.01
21	2.2 ± 0.37	2.7 ± 0.61	1.8 ± 0.02	1.4 ± 0.05	2.7 ± 0.01	3.3 ± 0.01
14	2.2 ± 0.29	2.8 ± 0.42	1.9 ± 0.01	2.2 ± 0.02	2.7 ± 0.01	3.3 ± 0.01
7	2.4 ± 0.13	3.0 ± 0.22	2.3 ± 0.02	2.8 ± 0.03	2.7 ± 0.01	3.3 ± 0.01
Ice-off	3.0 ± 0.09	3.3 ± 0.03	2.8 ± 0.15	3.3 ± 0.07	3.1 ± 0.02	3.3 ± 0.01

In 2006, the lake water column at the 10-m measurement location became isothermal on 18th April at 2.0 °C (±0.02) and at the 20-m location on 22nd April at 2.4 °C (±0.06) (Fig. 5). As in 2004, the bottom water temperature along the measurement transect was higher than the surface water temperature until the last week of the ice-covered period. A week before the ice-off the temperature difference between the bottom and surface water was 0.3 °C at the 20-m location. The mean temperature difference between the bottom and surface water at the 10-m location was 0.1 °C 14 and 7 days before ice-off. At ice-off, the daily mean temperature of surface water at the 10-m location exceeded the bottom water temperature, indicating the beginning of summer stratification.

Regardless of the initial water temperature at the beginning of the study period, the advective flow of warm water near the bottom from shallow regions towards the deep central region of the lake influenced the vertical distribution of water temperature along the measurement transect in both years. The increase in the surface water temperature triggering the water density change along the measurement transects was also strong (mean 1.5 °C and 2.2 °C in 2004 and 2006, respectively). The water column at the deepest location became isothermal on 24th April 2004 at 2.6 °C (±0.06), indicating under-ice turnover (Fig. 4). Despite the high incident radiation during the two last weeks of the ice-covered period, high air temperature and the presence of both vertical convection and advective flow in 2006, the under-ice mixing did not reach the bottom of the deepest location (Fig. 5). On the day of ice-off, mixing reached the depth of 65 m at the deepest location. The upper part of the lake started to stratify with no clear isothermal turnover.

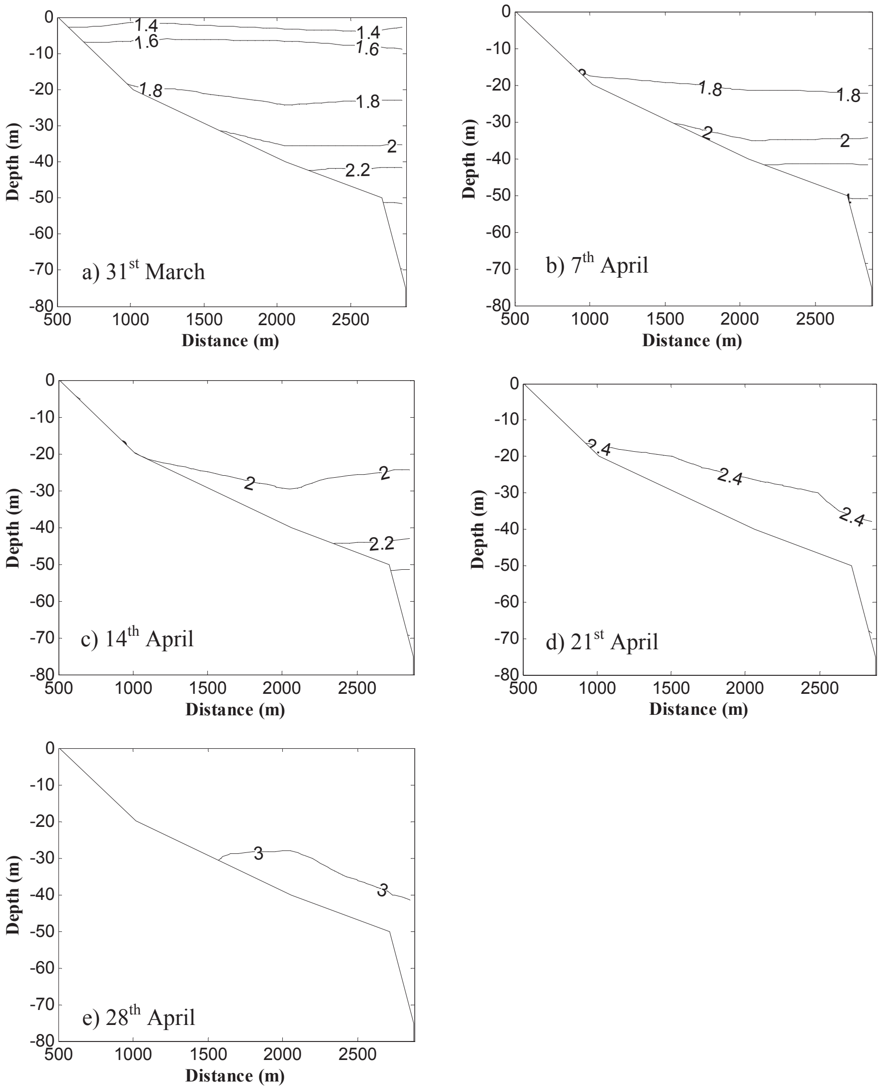

Figure 4. Evolution of daily mean water temperature (°C) along the north-western measurement transect of Lake Pääjärvi in 2004 at a) 4 weeks, b) 3 weeks, c) 2 weeks and d) 1 week before ice-off and e) on the day of ice-off. Figures are based on daily mean temperatures interpolated linearly between the measurement locations with 0.2 °C spacing.

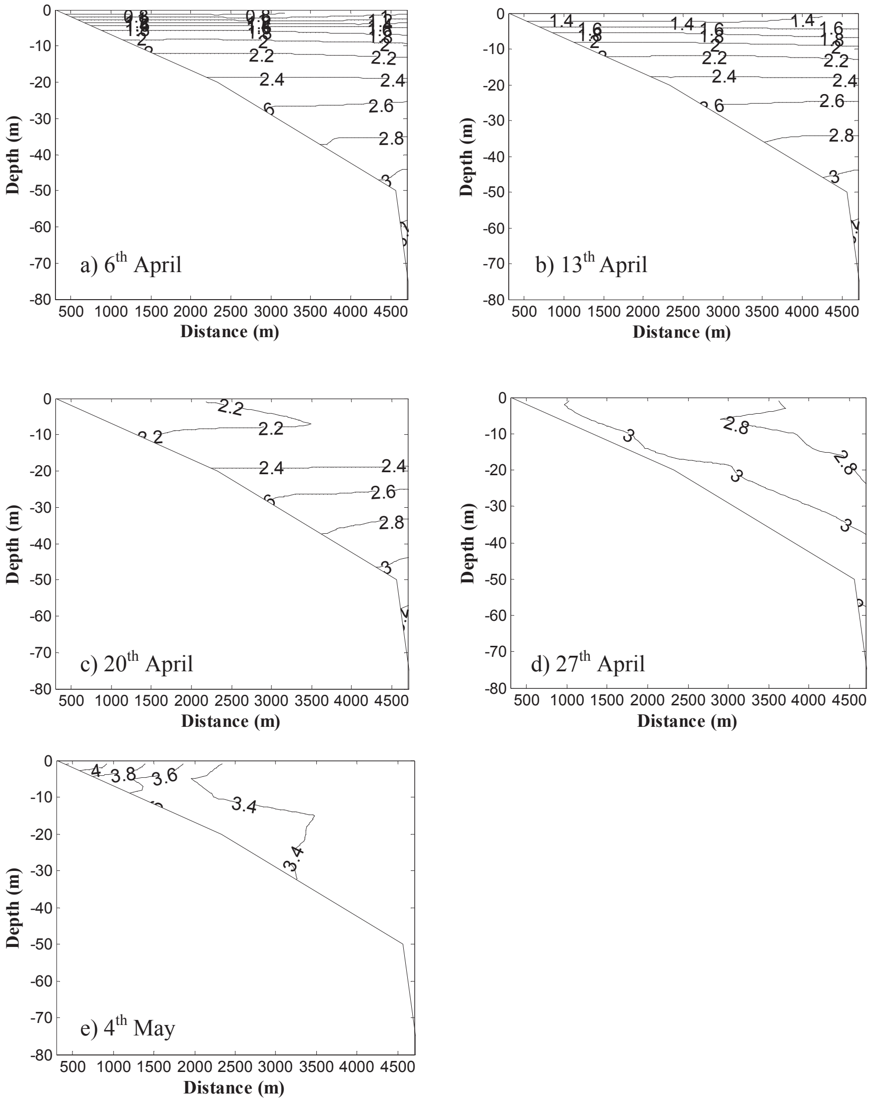

Figure 5. Evolution of daily mean water temperature (°C) along the western measurement transect of Lake Pääjärvi in 2006 at a) 4 weeks, b) 3 weeks, c) 2 weeks and d) 1 week before ice-off and e) on the day of ice-off. Figures are based on daily mean temperatures interpolated linearly between measurement locations with 0.2 °C spacing.

Discussion

The spring radiation conditions and the development of ice and snow cover strongly affect the evolution of lake water temperature. The structural development of lake ice cover is the key factor determining the physics of ice-covered lakes (Jakkila et al. 2009). Spatial differences and diurnal changes in the surface of the ice cover affect the amount of solar light passing ice and warming the water below (Adams 1981, Jakkila et al. 2009), which causes the vertical convection leading to the spring turnover of lakes. The duration and composition of the ice and snow cover varied between our study years; the snow cover existed longer and the superimposed ice layer was thicker in 2006, restricting the penetration of solar radiation at least in the first week of the study period. In 2006 due to the cloudy weather, the solar radiation during the first two weeks was lower than in 2004 and rapid warming of the water did not start until the solar radiation increased rapidly two weeks before the ice-off and the snow cover melted. Water colour affects the penetration of solar radiation into the water column. In brown-coloured humic lakes with high light attenuation coefficient, the solar radiation is absorbed within a thin water layer (Matthews & Heaney 1987). The stronger radiation during the last two weeks of ice cover and higher air temperature with greater water colour than in 2004, seem to trigger the rapid warming of the water in 2006.

Under-ice mixing along the measurement transect was associated with both vertical convection and advective flow of water along the bottom slope in Lake Pääjärvi. Stefanovic & Stefan (2002) found under-ice horizontal transport to be significant also in shallow Ryan Lake, with a maximum depth of 10 m. Under-ice thermal conditions vary annually and have spatial differences within a lake, with impact on the water hydrodynamics. The sublittoral region became isothermal two to three weeks before ice-off in the study years, after which the advective flow of warmed water affected the temperature distribution in the deep water layers of the deepest region of the lake. To characterize whole-lake ecosystem conditions, spatially and temporally diverse data are needed not only during summer (Van de Bogert et al. 2012) but also during the ice-covered period. In spring the nutrients accumulated over winter are available for the next growing season in lakes (Baehr & DeGrandpre 2004). Under-ice mixing affects the distribution of dissolved substances even before the ice-off; for example, dissolved oxygen concentration can become uniform in the whole water column if the lake undergoes under-ice turnover, as in 2004 in Lake Pääjärvi. In addition to nutrients, carbon and nitrogen gases accumulate during winter, and these stored greenhouse gases are released to the atmosphere after mixing of the lake water column and ice-off (e.g. Striegl & Michmerhuizen 1998, Huttunen et al. 2003a, Huttunen et al. 2003b, López Bellido et al. 2009).

In addition to their impact on biogeochemical cycles, under-ice temperature and mixing affect the distribution and development of biota. Water temperature determines the onset of hatching in fish species that spawn in the autumn (Valkeajärvi 1988, Urpanen et al. 2005). While the lake is still ice-covered in its central region, the water in the shallow region can be fully mixed and warmed rapidly due to both solar and, after the ice cover has melted, also thermal energy input. For instance, the hatching of autumn-spawning coregonids is well synchronized with the ice-off (Karjalainen et al. 2002, Urpanen et al. 2005) and their hatching is likely triggered by the advective flow of warm water from the littoral zone to their spawning sites in the sublittoral areas. Under-ice water movements also influence phytoplankton production and species composition (Matthews & Heaney 1987, Kelley 1997). The advective flow close to the lake bottom has been observed to affect the vertical distributions of phytoplankton in the deepest location of Lake Pääjärvi (Vehmaa & Salonen 2009).

Although the annual variation in both climatic factors and lake response is large, the impacts of global change on ice cover duration and structure are already noticeable. A trend of delay in ice-on and earlier ice-off in the Northern Hemisphere was found in ice formation and thawing records from 1846 to 1995 (Magnuson et al. 2000). Korhonen (2006) reported that the ice cover thickness has increased in Finnish lakes during the last 40 years, except in some lakes in southern Finland. The increase is related to thickening of the superimposed ice layers, because of the higher winter air temperatures and the increase in precipitation during the past four decades. Some climate models have projected further increases in winter precipitation in Finland (Jylhä et al. 2004), which has a two-fold effect on the warming of water at the beginning of thaw: more cloudy conditions and generation of lake ice with higher albedo limit the radiation penetrating into water.

Saloranta et al. (2009) simulated the future thermodynamic changes in lakes of different depth. The predicted changes towards higher autumnal and winter air temperature together with shortening of the ice-covered period can in fact lead to cooling of deep lakes in winter. The main heat fluxes causing water movements in Lake Pääjärvi during winter are the sediment heat flux and solar radiation penetrating the ice cover (Pulkkanen et al. 2013a/I). Although the length of the ice cover duration was similar in both study years, the water column temperature at the deepest location of the lake was lower in 2004 at the beginning of the study period. The effect of the preceding autumn conditions was seen even at the end of the ice-covered period; regardless of the greater increase in temperature, the water column temperature remained lower in 2004. The greatest seasonal increase in lake water temperature seems likely to be in spring in future. According to Pulkkanen et al. (2013b/III), cool water temperature favours the occurrence of under-ice turnover. If the lake stratifies soon after ice-off, as in 2006 in this study, the wind action in mixing may be restricted and gas exchange may remain limited. In addition, the higher spring water temperature may accelerate the overall metabolism of the lake ecosystem and have direct adverse effects on lake biota, such as on development of fish embryos adapted to cold water conditions (Cingi et al. 2010). Timing of the water warming is of importance to the response and adaptation of cold water species. As lakes are both affecting the climate and responding to climate change, more detailed knowledge about the under-ice conditions can assist in future lake management.

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