Article

Accumulation of low-oxygen water in deep waters of ice-covered lakes cooled below 4 °C

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Received 17 April 2012; accepted 19 December 2012; published 28 January 2013

Abstract

We studied vertical distribution of oxygen under the ice of 5 medium-sized, morphologically variable lakes that cooled well below 4 °C before freezing. In the upper part of the water column, dissolved oxygen and dissolved inorganic carbon concentrations generally remained vertically almost uniform, but in the deepest water, concentrations changed rapidly near the bottom. The coincidence of the changes with an increase in deep water temperature shows that they were due to advection of water made heavier by the heat flux from the sediment. Consequently, water with low concentrations of dissolved oxygen and high concentrations of dissolved inorganic carbon accumulated in the deepest part of the lake (i.e., outcome of sediment respiration on a large area was focused to a limited volume of the lake). This conclusion was supported by the results of an experiment in which water samples incubated at different depths showed no vertical differences in oxygen consumption. Our results show that temperature-dependent hydrodynamics affect under-ice oxygen conditions in medium-sized temperate lake basins. Interannual variation in water temperature and differences in morphology between lake basins probably cause significant variations in the accumulation of water in the deepest layers during winter.

Key words: dissolved inorganic carbon, dissolved oxygen, ice cover, sediment heat flux, water temperature

Introduction

Dissolved oxygen (DO) is one of the key elements affecting the chemical and biological characteristics of lakes (Wetzel 2001), and its concentration is controlled by dynamic physical, chemical, and biological mechanisms. Diffusion across the air–water interface and primary production provide oxygen for respiration and abiotic oxidation of reduced substances. In winter, ice cover isolates water from both supplies (Adams 1981), and oxygen-consuming processes in the lake rely predominantly on the amount of oxygen dissolved in water before freezing (Meding and Jackson 2001). Hence, oxygen may be depleted, which can release nutrients from the sediment (Mortimer 1941).

Under the ice, oxygen consumption is mediated by sediment bacteria and depends on the availability of organic matter, DO concentration, basin morphometry, and the duration of autumnal turnover (Mathias and Barica 1980). Most biological and chemical oxidation in lakes generally occurs in the sediment (Mathias and Barica 1980, Bastviken et al. 2003), and it also contributes to the development of DO concentration in water. Although low temperature limits biological and chemical activity in winter, oxygen can be consumed below the concentration of 2 mg L^{-1}, which triggers significant changes in the metabolic balance of lakes and may cause fish kills (e.g., Greenbank 1945, Wassenaar 2011).

In autumn, water temperature cools and eventually leads to isothermal conditions in the water column. Large lakes exposed to wind commonly cool below 4 °C, and water temperature is inversely distributed during winter. Due to the isolation of wind by ice cover, under-ice flow dynamics are often thought to be stagnant; however, Bengtsson (1996) listed water movements created by (1) through-flow of water, (2) wind-induced seiche, (3) heat

DOI: 10.5268/IW-3.1.514

flux from the sediment, and (4) solar radiation. These currents are slow (velocities <10^{-2} m s^{-1}) and therefore below the measurement threshold of standard mechanical current meters (Glinsky 1998). Instead of laborious tracer studies (e.g., Likens and Hasler 1962, Likens and Ragotzkie 1966, Colman and Armstrong 1987), indirect observations of temperature have generally been used to characterize and quantify the under-ice water movements (e.g., Birge et al. 1927, Mortimer and Mackereth 1958, Stewart 1972).

Fresh water density characteristics in temperature range 0–4 °C have an important consequence such that when water is heated, it gets denser. When heat stored during summer in the sediment is gradually released to overlying water (Birge et al. 1927, Mortimer 1942, Terzhevik et al. 2009), density gradient currents are generated flowing along the lake slopes toward the deepest location of the lake (Mortimer and Mackereth 1958, Welch and Bergmann 1985). Because medium and large lakes commonly cool below 4 °C during autumnal turnover, significant under-ice advective currents can occur. Along with this, oxygen consumption of the sediment decreases oxygen concentration in the overlying water (Mathias and Barica 1980), which is relocated by advective currents. Mortimer and Mackereth (1958) observed a significant increase in temperature in the near-bottom water layers of the deepest (169 m) location in Lake Torneträsk (322 km^2, Swedish Lapland) and associated that with advective currents. Regardless of the early recognition of the advection mechanism and the importance of DO to lake ecosystems, the effect of sediment of the whole lake on oxygen conditions in the deepest water layers has received surprisingly little attention.

Due to climate change, the duration of lake ice cover is predicted to shorten in the future. In the northern hemisphere, lake ice-off has occurred on average 1 week earlier and freezing has occurred 6 days later in a 100 year period (Magnuson et al. 2000). Extended length of autumnal mixing enhances the aeration of lakes and shortens the time that water remains isolated from the atmosphere by ice. Little is known, however, about how climate change affects heat exchange between water and sediment to evaluate the strength of under-ice advective currents toward lake deeps and its consequences on oxygen conditions.

We studied vertical distribution of temperature and oxygen in ice-covered lakes that reached a temperature well below 4 °C before freezing. We hypothesized that under such conditions, heat flux from the sediment induces variable lake-specific accumulation of water with low DO and high dissolved inorganic carbon (DIC) concentrations into deepest parts of lakes, which may have major consequences on the lake ecosystems.

Materials and methods

During winters 2004–2006, we studied the development of vertical DO and DIC concentrations as well as temperature in 5 dimictic lakes. Lakes Pyhäjärvi, Iso-Roine, Päijänne, and Pääjärvi are medium-sized boreal lakes in southern and central Finland, and subarctic Lake Kilpisjärvi is located in north-western Finland (Table 1).

With the exception of Lake Iso-Roine, the mean depths of the study lakes were greater than average for Finnish lakes (7 m; Finnish Environment Institute). Lake Iso-Roine is an oligotrophic lake with significant through-flow in its deepest location. The lake has a large shallow area with few deep sites so that only about 25% of its area is deeper than 10 m (Fig. 1). Lake Pyhäjärvi is classified as a clay-turbid, eutrophic lake with kettle-shaped bottom topography. Lake Päijänne, the second largest lake in Finland, has several large basins. Our measurements were made in the deepest site of inland waters in Finland,

Table 1. Location and basic characteristics of the study lakes (Database of the Finnish Environment Institute). Data not available: n.a.

Lake	Location (WGS-84)	Elevation (m a.s.l.)	Surface area (km^2)	Mean depth (m)	Max depth (m)	Retention time (years)
Iso-Roine	61°12.5 N 24°35.6 E	84	30.9	7.2	73	n.a.
Northern 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	13.0	20.8	68	n.a.
Pääjärvi	61°03.4 N 25°07.5 E	103	13.4	14.8	85	3.3
Kilpisjärvi	68°56.2 N 20°50.8 E	473	37.3	19.5	57	8

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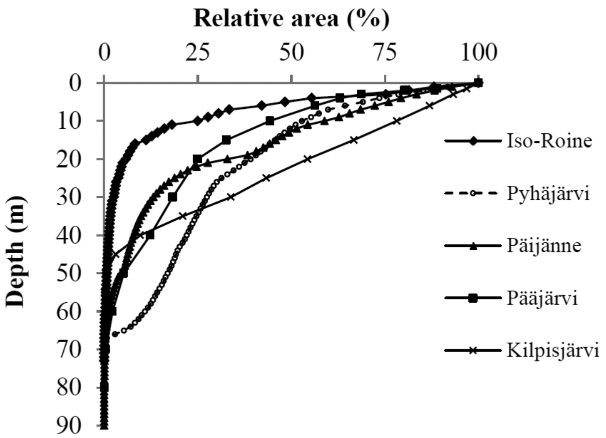

Fig. 1. Relative area to depth profiles of the study lakes.

Ristinselkä basin, which has steep bottom topography. Currently, northern Lake Päijänne is meso-oligotrophic, but its water quality is considerably affected by an upstream pulp mill. Lake Pääjärvi is meso-oligotrophic with steep sides at the deepest location. Its >50 m depth zone is 5.2% of the lake area. Lake Kilpisjärvi is a subarctic clear-water lake classified as ultra-oligotrophic. The measurements were made in the northern basin, which is connected to the southern basin of the lake by a narrow channel. About 60% of the lake area is >30 m deep, but its bottom topography is much more irregular than in the other study lakes.

Sampling and measurements were started 1–3 months after the formation of ice cover. Water temperature profiles for calculations of DO saturation were measured from the deepest locations of the lakes with Starmon Mini recorders (Star-Oddi, Iceland; accuracy ±0.05 °C), or with a conductivity–temperature–depth profiler (Micro CTD, Falmouth Scientific, USA; temperature accuracy ±0.005 °C). In winter 2005, temperatures in lakes Pyhäjärvi and Iso-Roine were measured with a thermometer (accuracy ±0.5 °C) attached to a Limnos tube sampler. Temperature recorders were attached to a rope at 1 m, 5 m, and thereafter at 5 m depth intervals down to the lake bottom. The weighted rope was connected to a subsurface float. In winter 2006, temperature was also measured with Starmon Mini recorders from the sediment at a depth of about 0.12 m, from the near-sediment water layer in the western bay of Lake Pääjärvi (depths 20.7 and 20 m, respectively), and in the deepest location (depths 78.6 and 75 m, respectively), 2.3 km apart.

Unfortunately, temperature measurements with recorders were not always successful. Missing temperature data as well as water colour data for detection of groundwater discharges to the lakes were obtained from the database of the Finnish Environment Institute.

Water samples were taken about once a month from the same depths where temperature was measured. During a more detailed survey in early winter 2006 in Lake Pääjärvi, water samples were also taken before and soon after the complete formation of ice cover. DO was determined by Winkler method with an automated titrator (Mettler Toledo DL 53), and DIC with acidification and bubbling method using infrared detection of CO_2 (Salonen 1981). In Lake Pääjärvi, DO consumption in the water column was also determined by incubating water samples in the lake over the winter in darkened 50 mL ground-glass-stoppered bottles at the sampling depths (Table 2).

For each lake, we compared the DO and DIC concentrations to concentrations at a reference depth where no primary production was assumed and where decrease of DO due to the sediment oxygen consumption would be minimal in winter. In practice, at that depth, water temperature showed the least change before the beginning of spring convection.

The oxygen saturation relative to lake surface pressure was calculated with equations (APHA 1985):

$$\ln P = 5.25 \ln (1 - 44.3^{-1} h), \quad (1)$$

where P is the nonstandard pressure (atm) at altitude h (km) relative to standard partial pressure at 101.325 kPa at sea level, and

$$C_p = C^* P [(1-P_{wv}P^{-1})(1-\theta P)((1-P_{wv})(1-\theta))^{-1}], \quad (2)$$

where C_p is the equilibrium oxygen concentration at nonstandard pressure (mg L^{-1}); C* is the equilibrium oxygen concentration at standard pressure (mg L^{-1}); P is the nonstandard pressure (atm); P_{wv} is the partial pressure of water vapor, calculated with $\ln P_{wv} = 11.8571 - (3840.70T^{-1}) - (216.961T^{-2})$, where T is the ambient temperature in K); and θ is calculated with $0.000975 - (1.423 \cdot 10^{-5}\ t) + (6.436 \cdot 10^{-8}\ t^2)$, where t is the ambient temperature in °C). Finally percent saturation was calculated according to the equation

$$\text{DO saturation (\%)} = 100\ \text{DO} \times C_p^{-1}, \quad (3)$$

where DO is determined oxygen concentration.

Table 2. Dates of ice-on and starting dates of the *in situ* oxygen consumption incubation tests and their duration in Lake Pääjärvi.

Winter	Ice-on	Incubation	Duration (days)
2003/2004	21 Dec	12 Feb	68
2004/2005	13 Dec	3 Jan	106
2005/2006	22 Dec	10 Jan	107

Results

In the study lakes, under-ice water temperature was inversely distributed and consistently <4 °C throughout the study period (Fig. 2). No clear coherent pattern in water temperature profiles was observed between the study lakes located in southern Finland. For example, in winter 2005 lakes Iso-Roine, Pyhäjärvi, and Päijänne froze completely only in late January to early February, and their under-ice temperatures were subsequently very low. At the same time, Lake Pääjärvi had already frozen over in December 2004, although its surface area is similar to that of Lake Pyhäjärvi.

Continuous records from the deepest location of Lake Pääjärvi showed constant but small increases in temperatures both above and within (0.12 m) the sediment during

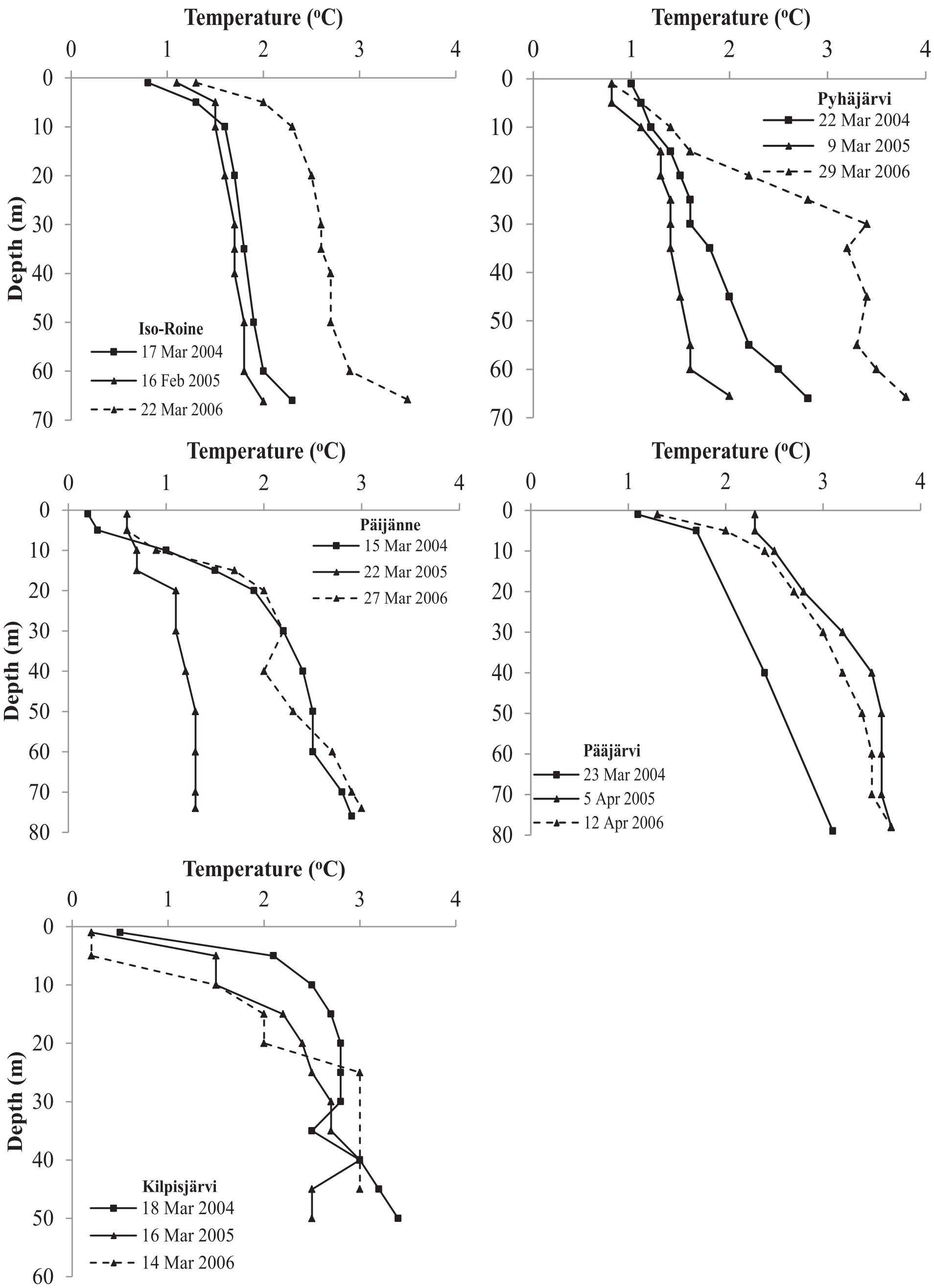

Fig. 2. Midwinter temperature profiles of the study lakes in 2004–2006 (Database of the Finnish Environment Institute).

DOI: 10.5268/IW-3.1.514

winter (Fig. 3a). Instead, in the sediment of the 20 m site, the respective temperature decreased 0.6 °C from freezing to the end of March, but above the sediment it increased 0.1 °C.

During autumnal cooling in December 2005, the DO concentrations of Lake Pääjärvi were vertically almost uniform and increased until the freeze-over of the lake (Fig. 3b). Three weeks after lake freezing, decreased DO concentrations were observed in the lowermost 10 m of the water column. Thereafter, the same trend continued, and the low DO zone gradually moved upward so that by the end of March it was located 25 m above the bottom. In all study lakes, DO saturation fell to 50–60% in the vicinity of the sediment, while in the upper part it remained close to 90% (Fig. 4).

In lakes Iso-Roine, Pyhäjärvi, and Pääjärvi the reference depth with minimal change in temperature and DO during winter was 30 m, in Lake Päijänne 40 m, and

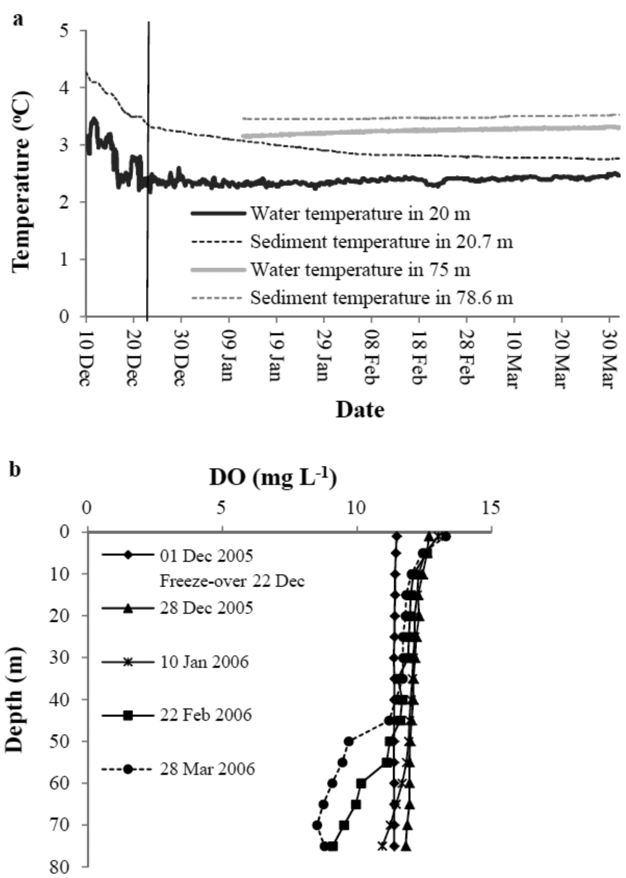

Fig. 3. (a) Development of temperature at ~0.12 m depth in the sediment surface and in the overlying water in Lake Pääjärvi during winter 2006. Lake freezing (22 Dec 2005) is indicated by a vertical line. (b) DO concentrations in Lake Pääjärvi in winter 2006.

in Lake Kilpisjärvi 20 m. With the exception of the depth of 1 m, the ratio between observed and reference depth DO and DIC concentrations in the upper part of the water column of all study lakes was relatively stable and close to one (Fig. 5–7). Occasionally, the near ice reference depth ratios showed values >1 in DO and <1 in DIC in late winter, which was most likely due to under-ice photosynthetic activity (Vehmaa and Salonen 2009) or melt water from snow and ice. Below the reference depth the ratio started to change, and in lakes Pyhäjärvi, Päijänne, and Kilpisjärvi, it was most pronounced within the deepest 5–15 m of the water column (Fig. 5 and 6). In Lake Pääjärvi, the significant decrease of DO and increase of DIC concentration occurred in a thicker (~25 m) layer (Fig. 7). The same development was repeated every year, so it seems to be typical of Lake Pääjärvi rather than a random occurrence. In Lake Iso-Roine the situation was different from the other lakes because the ratio between observed and reference depth DO did not show any layer with vertically uniform values (Fig. 5). In some measurements with the CTD profiler, temperature and conductivity anomalies in intermediate water layers were also observed (results not shown). The measurement site was near an inlet from an upstream lake, and hence the vertical distributions of DO and DIC were probably affected by inflow. Further, in contrast to the other lakes, between late February and March DO and DIC concentrations below the reference depth remained at the same level, indicating significant water exchange (Fig. 5).

During winter, the lake water colour remained the same in the whole water column or showed an increase toward the bottom (Table 3). Thus, because groundwater in these regions was by far less coloured than the surface water, the dilution of lake water colour by groundwater discharge was not detectable in the deepest parts of the study lakes.

In contrast to stronger decreases in DO and increases in DIC concentration toward the bottom in Lake Pääjärvi, DO consumption in bottled water samples incubated at their sampling depths showed no vertical trend (Fig. 7). During winters 2004/2005 and 2005/2006, the mean DO consumption in the incubations was 0.008 g m^{-3} d^{-1} (SD ± 0.002 and ± 0.003, respectively). In 2006 the mean consumption was lower, 0.003 g m^{-3} d^{-1} (SD ± 0.001), but again there was no vertical trend. In 2004/2005 and 2005/2006, the respective *in situ* decrease in DO concentration of the 5–30 m water layer was practically identical to that measured in bottle incubations (Table 4). Instead, in the 55–70 m water layer the respective decrease was 3–4 times higher.

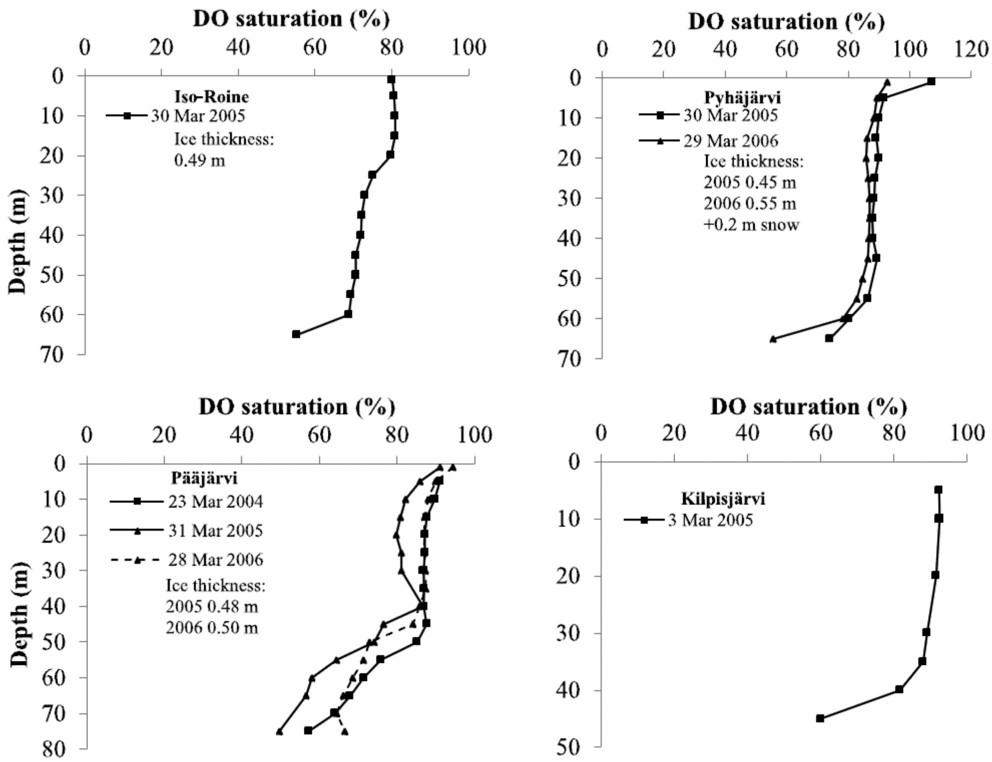

Fig. 4. Midwinter DO saturation in the study lakes.

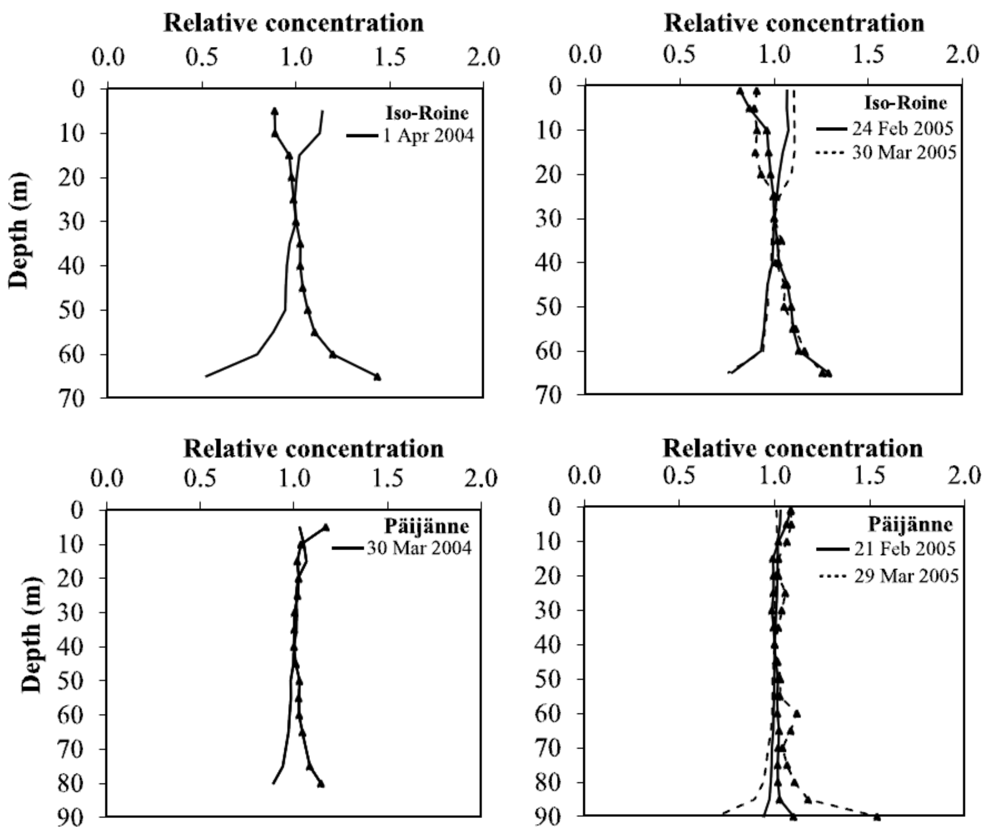

Fig. 5. Concentrations of DO (line) and DIC (line with triangles) in Lake Iso-Roine compared with concentrations at the depth of 30 m, and in Lake Päijänne compared with concentrations at the depth of 40 m in 2004–2005.

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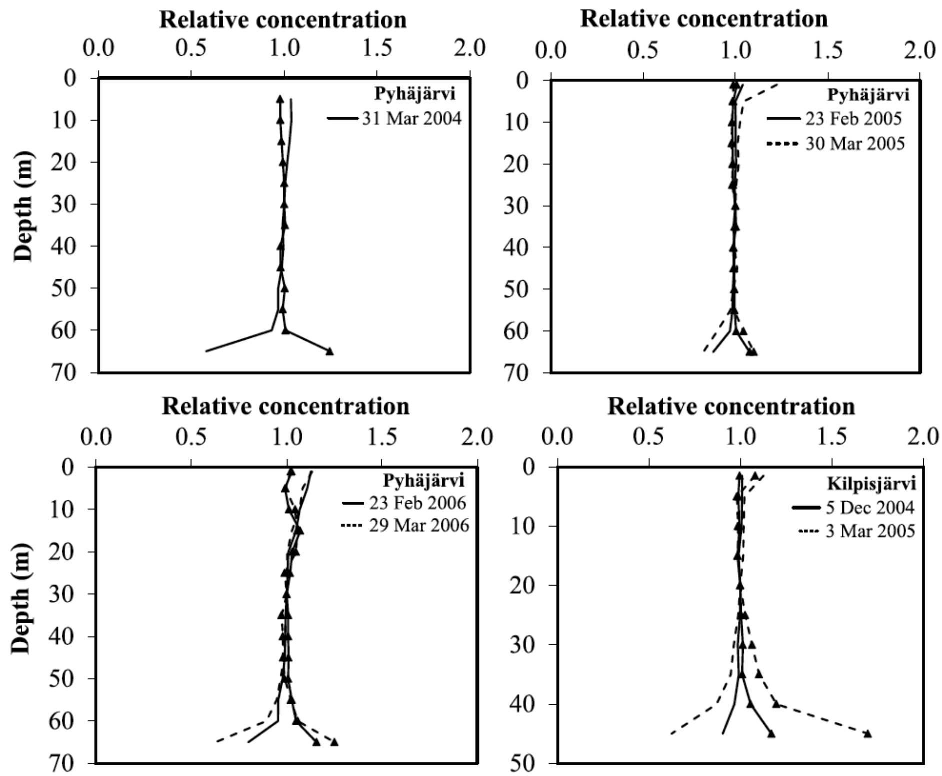

Fig. 6. Concentrations of DO (line) and DIC (line with triangles) in Lake Pyhäjärvi compared with concentrations at the depth 30 m and in Lake Kilpisjärvi compared with concentrations at the depth of 20 m in 2004–2006.

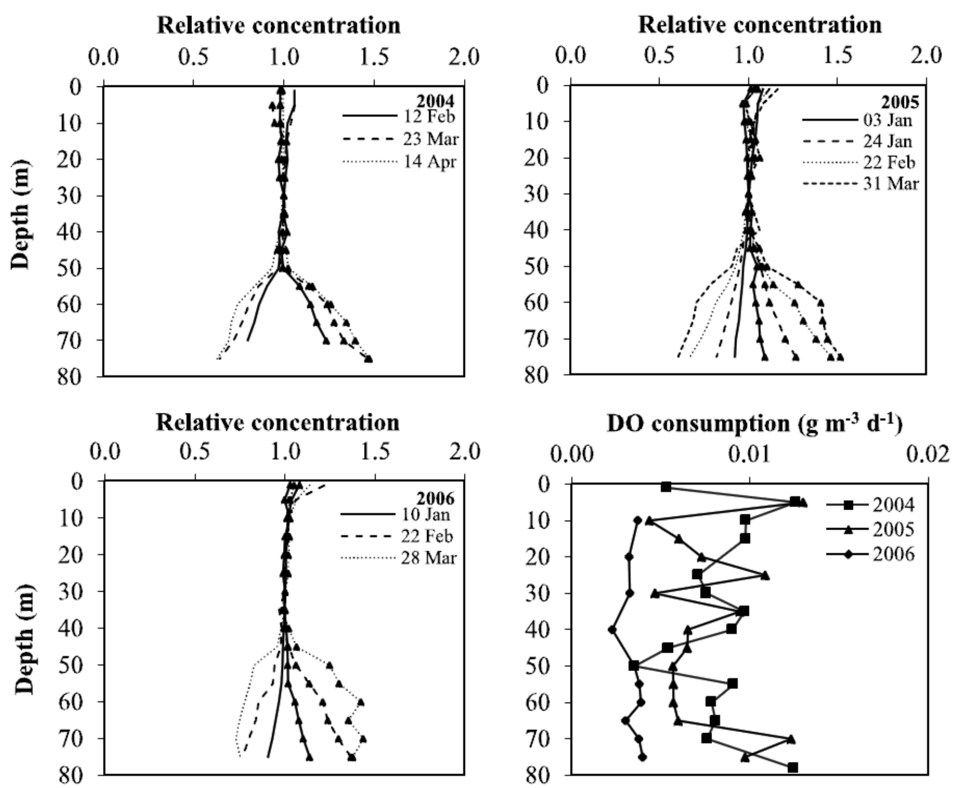

Fig. 7. Concentrations of DO (line) and DIC (line with triangles) in Lake Pääjärvi compared with concentrations at the depth of 30 m and vertical distribution of DO consumption during midwinter 2004–2006.

Table 3. Water colour (mg Pt L^{-1}) in the surface (depth of 1 m) and above the bottom (lake-specific; 1–9 m) of the study lakes before the melting phase of ice in Mar–Apr 2004–2006 (Database of the Finnish Environment Institute). Data not available: n.a.

Lake	2004 Surface	2004 Bottom	2005 Surface	2005 Bottom	2006 Surface	2006 Bottom
Iso-Roine	10	20	23	28	25	25
Northern Päijänne	40	25	60	35	50	35
Pyhäjärvi	70	100	140	160	100	180
Pääjärvi	45	45	80	80	70	74
Kilpisjärvi	n.a.	n.a.	5	5	8	8

Table 4. Midwinter decrease in oxygen concentration (g m^{-3} d^{-1}, ±SD) in water layers above (5–30 m) and below (55–70 m) the depth with minimum temperature change and its comparison to the results of obtained from bottles incubated in situ in Lake Pääjärvi. n = number of depths of oxygen determinations; L:B = lake median to bottle mean oxygen decrease ratio.

Layer	Median	Mean	n	L:B
12 Feb to 14 Apr 2004 – 62 days				
5–30 m	0.007	0.008 ± 0.04	6	1.0
55–70 m	0.025	0.024 ± 0.05	4	3.0
3 Jan to 31 Mar 2005 – 106 days				
5–30 m	0.008	0.008 ± 0.002	6	1.1
55–70 m	0.032	0.048 ± 0.036	4	4.3

Discussion

In lakes where wind together with air temperature determines vertical mixing, water temperature during autumnal turnover falls below 4 °C and causes advective currents. In addition to heat flux from the sediment, discharges of rivers and springs can also cause flow of warm water along the sediment surface toward the deepest parts of the lake after freezing. Although we studied neither of these directly, some conclusions are possible. Temperatures of discharges from snow- and ice-covered rivers are typically low during midwinter, and due to the inverse temperature distribution of under-ice lake water, the river inflow affects mainly surface water temperatures beneath the lake ice. This was strikingly demonstrated in the results of northern Lake Päijänne, where the highest water colour was observed in the upper water layers, which receive a high load of humic effluents from the upstream pulp mill.

Groundwater temperature is near the annual mean air temperature (Anderson 2005) of 4.2 °C (1981–2010) at the weather station close to Lake Pääjärvi (Pirinen et al. 2012). If the heat accumulation by groundwater is significant, its low colour compared to study lakes should lead to a dilution of the colour of the lake water. No decreasing trend in colour with increasing depth could be detected even in Lake Pääjärvi, however, which is the most humic of the study lakes and where deep water heat accumulation was also most striking. We therefore conclude that significant contribution of river water (with the exception of Lake Iso-Roine) or groundwater to deep water warming can be excluded in Lake Pääjärvi and does not seem likely in the other lakes.

In agreement with the results of Mortimer and Mackereth (1958), the concurrence of the decrease in DO concentration, increase in DIC concentration, and the accumulation of heat in the same deep water layers of Lake Pääjärvi provide strong evidence that deep water DO concentration is affected by horizontal advection of water. This conclusion was further supported by the incubation experiments, which, in contrast to the observed *in situ* concentrations, showed no vertical differences in DO consumption. Thus, oxygen consumption across the large sediment area of the lake appears in a smaller area and volume around the deepest site (i.e., at some distance from the original location where oxygen was consumed). Compared with respiration in ambient water, this greatly accelerates the depletion of deep water oxygen. Many substances, such as nutrients leaking from the sediment, can also be focused into the deepest parts of the water column. In oligo- or mesotrophic lakes, oxygen consumption is not as dramatic as in eutrophic lakes but still can play a significant role. The observed accumulation of water with low oxygen concentration into the deepest parts of lakes is a mechanism that amplifies the changes in redox conditions in lake deeps (Mortimer 1941) and hence may accelerate eutrophication by enabling increased nutrient leakage.

The large differences in the thickness of the layers in which warm water accumulated among our study lakes suggest that, in addition to sediment oxygen consumption, morphometric features may be important in the development of oxygen depletion in the deepest parts of lakes. The thick heated layer at the bottom of Lake Pääjärvi can be explained by a relatively small deep-water area and by steep and consistent topography (Fig. 1 and 2). For example in lakes Kilpisjärvi, Pyhäjärvi, and Päijänne, the relative volume of deep water is larger than

 DOI: 10.5268/IW-3.1.514

in Lake Pääjärvi and therefore probably contributes to a less distinguished warm water accumulation layer. In addition to morphometry, the weather conditions before freezing are important. Particularly, temperature reached during autumnal turnover may affect the heat flux between sediment and water (Bengtsson 2011).

Due to large variations in water temperatures (Fig. 2) and in freezing times of lakes among winters, warming of water overlying lake sediment is a complex issue. Although deep water temperature of medium- and large-sized lakes generally varies within a narrow range of 1–4 °C, such small differences may significantly affect sediment respiration, which is strongly temperature limited (Bergström et al. 2010, Gudasz et al. 2010). Further, the nonlinear increase in temperature-specific density of water below 4 °C means that at different temperatures the same heat flux from the sediment produces markedly different density gradients in the overlying water and hence determines the strength of advection and its effect on oxygen concentration.

Small changes in temperature due to climate change may therefore also be significant. The evident delay in freezing (Magnuson et al. 2000) shortens the ice-covered period and therefore reduces cumulative oxygen consumption. Golosov et al. (2007) speculated that warming leads to increased heat storage in the sediment. However, this effect does not necessarily persist until the development of ice cover. Because solar radiation is low around the winter solstice at high latitudes, delayed autumnal turnover may allow more time for cooling of water and sediment and may actually lead to lower under-ice temperatures (Saloranta et al. 2009) and reduced respiration. In fact, in the 40-year observations made at northern Lake Päijänne (Database of the Finnish Environment Institute), the record low temperatures (around 1 °C) in the 90 m water column were observed in 2005 and 2007 when the lake froze exceptionally late. Low water temperature may support density gradient driven advection of water above the sediment, but temperature gradient is also essential. Large datasets on water temperature, particularly the temperature gradient between sediment and water, during the autumnal cooling period and winter are required for comprehensive evaluation of the role of the focusing of low oxygen concentration into the deep water. This information is needed from a variety of lakes and over many years.

Acknowledgements

This study was financed by the Academy of Finland (Grant 104409). We warmly thank Prof. R.I. Jones and Prof. J. Karjalainen for comments on this manuscript, and Mr. J. Seppänen for assistance in field work during 2004.

We warmly thank the referees, editors and Prof. R.I. Jones and Prof. J. Karjalainen for comments on this manuscript, and Mr. J. Seppänen for assistance in field work during 2004.

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