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Diverging site-specific trends in the water temperature of a large boreal lake in winter and summer due to mixed effects of local features and climate change

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We present diverging long-term trends in the water temperature of a large boreal lake, Lake Pyhäselkä (263 km^2), located in eastern Finland. The dataset was constructed from a half century of monitoring (1962–2010). The direction of the temperature trend depended on the water layer and the season, in that the yearly average temperature in the top layer (1–10 m) as recorded in summer (June–August) increased by 2.5 °C over the monitoring period, whereas that recorded when the lake was covered by ice (January–April) decreased from 0.6 to 0.2 °C. The water temperature in the bottommost layers showed no trends. We suggest that the water temperature under the ice is decreasing in this case as a consequence of mixed effects of lake-specific physical features and climate change, which cause variations in the heat content of the inflowing water of the Pielisjoki. The epilimnetic water temperature in summer appeared in turn to follow general trends in air temperatures. Our results stress the need for taking local and site-specific phenomena into account when drawing conclusions about the effects of climate change on lakes.

Introduction

The effects of climate change on freshwater ecosystems will probably be most unpredictable in the boreal region of Canada, in northern Europe and in Russia (Magnuson *et al*. 1997, Blenckner *et al*. 2010), where the warming of surface waters will take place faster than elsewhere (Schneider and Hook 2010) and most of the lakes are thermally stratified in summer and covered by ice for several months in winter. The strength of the summer thermal stratification, i.e. the temperature (and density) difference between the upper and lower water layers, affects the timing and length of the water circulation in autumn, which plays an important role in oxygenating the bottommost water layers. The lake ice and snow cover in winter then causes disruption in the normally rather straightforward relationship between air and surface water temperatures

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through thermal buffering, leading to the "winter anomaly", (Blenckner and Chen 2003, Saloranta *et al*. 2009). Consequently, when studying the effects of climate change on boreal lakes it is of special importance to take into account the very different circumstances prevailing in these two periods, the summer stratification and the winter ice cover (Järvinen *et al*. 2002).

Concrete effects of the ongoing climate change on inland waters have already been detected and demonstrated in Europe (Scheffer *et al*. 2001), North America (Schindler *et al*. 1996) and Africa (Verburg *et al*. 2003). Winter air temperatures and precipitation rates in Europe have progressively increased since the 1980s in correlation with changes in the large-scale meteorological phenomenon known as the North Atlantic Oscillation (NAO) (Hurrell 1995). In years when the difference in atmospheric pressure between Iceland and the Azores is high (the NAO index is positive), westerly winds bring moist air to Europe, which leads to high precipitation rates, mild winters and cool summers (*see* Hurrell *et al*. 2003 for a review). This has a significant effect on both large-scale and more regional weather conditions (Hurrell 1995, Hurrell and van Loon 1997), and both terrestrial and aquatic ecosystems (Ottersen *et al*. 2001).

In contrast to central Europe, the main manifestation of the ongoing climate change in Finland, which is located in the boreal region, will not necessarily be an increase in air temperature but an increase in precipitation rate (Mellert *et al*. 2008), but despite this, many Finnish lakes and their surrounding areas, but not all, show a tendency for water temperatures to rise (Hyvärinen 2003) and the duration of the ice cover to diminish (Magnuson *et al*. 2000). These multiple climate-related changes are expected to cause great variations in lake dynamics (e.g., George *et al*. 2007) especially in the boreal region, where the lakes have also undergone modifications which are not directly related to climate change, including active water level alterations owing to the production of hydroelectric power and flood damage prevention, for instance. Local lake–river interactions are particularly important in winter and spring, when incoming river water may affect the circulation patterns and heat budget of the recipient lake and thus modify its ecology (Carmack *et al*. 1979).

We present here a unique dataset constructed from 50 years of observations on water temperatures in a large boreal lake, Lake Pyhäselkä, located in eastern Finland, and 80 years of observations on the regional climate. The aims are firstly to reveal possible trends in the parameters monitored, secondly to focus on possible trends and variations in water temperature related to those in climate, and thirdly to study the effects of the Pielisjoki, a river which flows into Lake Pyhäselkä, on the detailed thermal conditions of the lake under the winter ice by calculating the river heat flux. We also report the results of measurements carried out with an ultrasonic current meter (UCM) in winter 1994 with the aim of constructing an under-ice water current field for the northern part of Lake Pyhäselkä. These UCM results have not been published elsewhere, and they help us to draw certain conclusions from the present findings.

Material and methods

Study site

Lake Pyhäselkä is a large (263 km^2), humic, brown-water (average water colour 82 mg Pt l^{-1} in 2009) lake situated in Eastern Finland (62°20´–62°40´N, 29°33´–29°56´E). Its average and maximum depths are 9 and 67 m, respectively, and the theoretical water retention time is 3.5 months. The drainage basin of Lake Pyhäselkä (24 340 km^2) was covered by boreal forest in historical times, with Scots pine, *Pinus sylvestris*, and Norway spruce, *Picea abies*, being the dominant tree species. The area has been modified by human activities (especially the sawmill industry) since the 19th century. Joensuu, the only relatively large town in the drainage basin area, was founded in 1848, and its population in 2010 was ca. 73 000. Lake Pyhäselkä has been receiving purified effluent from one of the largest pulp mills in the world, the Enocell Mill, through the Pielisjoki since 1967. The river itself is 67 km long and flows through the city of Joensuu into the northern part of Lake Pyhäselkä. It has been modified by several man-made canals and its flow is regulated by two hydroelectric power

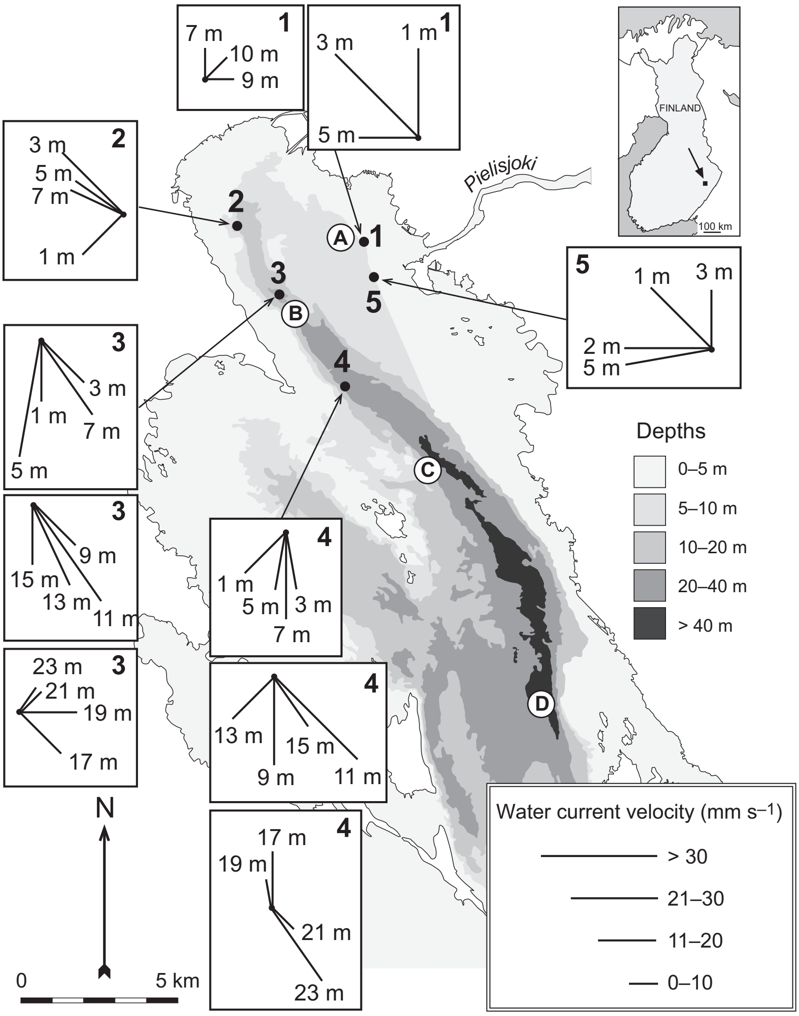

Fig. 1. Location of Lake Pyhäselkä and the Pielisjoki in Finland, showing the four sampling sites where water temperatures were measured in 1962–2010 (A = Noljakansaaret, B = Kaskesniemi, C = Pyhäsaari, D = Kokonluoto). The figure also shows water current vectors as measured on 29 and 30 March 1994. The lines within each rectangle represent the velocity vectors starting from the origin. The measurement depth is indicated at the end of each line. Numbers 1 to 5 indicate the sites where water currents were measured.

plants, located at Kaltimonkoski (completed in 1958) and Kuurna (completed in 1971), about 40 and 20 km from the river mouth, respectively. Mean discharge of the river in 1962–2011 was 239 m^3 s^{-1}. The production capacity the Enocell Mill is nowadays 450 000 tonnes of bleached softwood pulp per year. The purification plants that treat the municipal sewage from Joensuu and the pulp mill effluents from Enocell were modernized in 1987 and 1992, respectively, and this has considerably reduced the nutrient loading into Lake Pyhäselkä, and helped the lake to recover, and regain some of its pristine water quality. For a detailed description of long-term changes in the lake's water quality, *see* Voutilainen and Huuskonen (2010).

Lake water currents

Here, we use unpublished water-current data obtained by Huttula and Ylinen with an ultrasonic current meter (UCM50, Sensortec A/S, Norway) on 29 and 30 March 1994 in connection with work funded by the North Karelian Regional Environmental Centre. The purpose was to trace the movements of water from the Pielisjoki in the northern part of Lake Pyhäselkä, and the measurements were carried out at five locations (Fig. 1), which were different from those where water temperature was measured between 1962 and 2010. The accuracy of the current meter was 1 mm s^{-1} and that of the water temperature sensor 0.01 °C. At the time of the

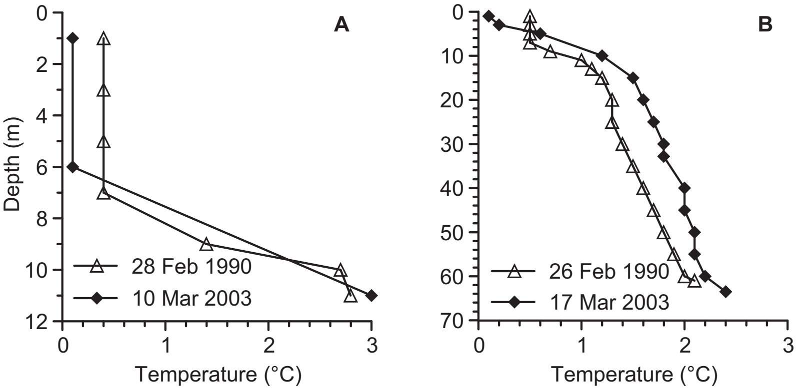

Fig. 2. Winter under-ice thermal stratification at (**A**) the shallowest sampling site, located close to the river mouth at Noljakansaaret, and (**B**) the deepest site, ca. 15 km south of the river mouth at Kokonluoto.

measurements in March 1994, Lake Pyhäselkä was covered by ice and its water level was 75, 85 m + N60, i.e. 2 cm above normal. The inflow from the Pielisjoki was 156.5 $m^3 s^{-1}$, corresponding to the long-term average inflow in March. The outflow value of Lake Saimaa at the same time was 623 $m^3 s^{-1}$, which is somewhat higher than the long-term average value for March (595 $m^3 s^{-1}$). The thickness of the ice on Lake Pyhäselkä varied spatially between 70 and 80 cm and the snow depth between 30 and 40 cm. For the present measurements, the meter was lowered to the desired depth through a hole in the ice, and water temperature and currents were recorded for a period of 2–3 min after a stabilization interval of 30 s. The mean current value for this period was taken as the speed of the water at that particular site and depth for the purposes of the later analyses. The measurements were carried out at 1 m depth intervals.

Analysing trends in water temperature

Long-term water temperature measurements have been carried out at four sampling sites in Lake Pyhäselkä, Noljakansaaret (maximum depth 13 m), Kaskesniemi (38 m), Pyhäsaari (53 m) and Kokonluoto (65 m) (Fig. 1) each year between March 1962 and March 2010. For the present survey, annual average summer water temperatures in the lake were calculated on the basis of the temperatures measured at each sampling site once or twice per year between 24 June and 31 August, and annual average winter water temperatures on the basis of those measured once or twice per year between 1 January and 30 April. During these periods the water column in the lake is in general thermally stratified, having a clinograde (summer) or orthograde (winter) temperature profile. The reverse temperature stratification in winter is shown in the figures for the shallowest sampling site, Noljakansaaret (Fig. 2A), and the deepest sampling site, Kokonluoto (Fig. 2B). The lake is covered by ice in winter.

The temperature data were divided into two groups representing the upper and lower water layers, determined on the basis of the temperature profiles. The upper water layers are referred to below as the top layer when speaking about both summer and winter conditions, and as the epilimnion when referring only to summertime conditions. Correspondingly, the lower water layers are termed the bottom layer when referring to both summer and winter and the hypolimnion when referring only to summer. In the case of the top layer, the data consisted of temperature measurements taken at intervals of 1–2 m between the depths of 1 and 10 m. Thus the total calculated number of top layer measurements per site was 490 when taken at intervals of 1 m (ten measurements between the depths of 1 and 10 m repeated over 49 years) and 245 at intervals of 2 m (five measurements repeated over 49 years). In practice, the final number of top layer temperature measurements per site was smaller than 240 in the case of Kaskesniemi (winter), Pyhäsaari (winter) and Kokonluoto (winter and summer) (Table 1) due to missing years and/or single measurements. The maximum number of missing values per site was 22 (Kokonluoto in winter). Since the missing years/single measurements were randomly distributed, their potential effect on the trends in water temperature was minor. In the case of the bottom layer, the data consisted of measurements taken at intervals of 2 to 5 m between a depth of 15 m and the bottom. The bottom layer data did not include temperature measurements taken at Noljakansaaret due to the shallowness of the sampling site. As the total number of bottom layer measurements taken varied between the sites (Table 1), because of their unequal depths, the annual average temperatures representing the whole lake were calculated from the site-specific averages. The data were gathered from the OIVA database (accessed between 8 September 2010 and 24 January 2011) maintained by the Finnish Environment Institute.

Calculating the stability of the lake and the heat flow from the river

Schmidt stability (Schmidt 1928) was calculated for the shallowest water temperature measurement site, located close to the river mouth at Noljakansaaret, and for the deepest site, located ca. 15 km south of the river mouth, at Kokonluoto, on the basis of water temperature profiles with a simple computer programme provided by the Finnish Environment Institute, and written by Petri Kiuru in 2010. Schmidt stability indicates the stability of a water body and its resistance to mixing. Schmidt himself defined it as the additional work that would be required to transform the current density distribution into a new one without adding or subtracting heat (Schmidt 1928, Sherwood 1973).

The heat flux (W) of the river was calculated for each day for which water temperature measurements were available by multiplying water temperature by river water mass. The density of the water was expected to be 1000 kg m^{-3}. River water temperatures and discharge have been measured at several locations with varying regularity since the establishment of the hydroelectric power plants at Kaltimonkoski in 1956 and Kuurna in 1971. For the present calculations, we used water temperatures measured at Kaltimonkoski in 1963–2011 and Utra (about 8 km from the river mouth) in 1972–2011 and discharges measured at Kaltimonkoski in 1963–2011 and Kuurna in 1972–2011.

Analysing trends in climate

Air temperature, precipitation and snow cover thickness in the Lake Pyhäselkä area have been monitored since 1933 up to the present without any breaks. The station responsible for monitoring weather in the area, excluding precipitation, is situated at the Joensuu Airport, about 3 km north of Lake Pyhäselkä. The station measuring precipitation lies about 20 km north of the lake, at Jakokoski, close to the Pielisjoki. For the present purposes, values for the above climatological parameters were gathered from the monthly weather reports published by the Finnish Meteorological Institute. These reports provide monthly average air temperatures, amounts of rainfall, i.e. precipitation, and average thicknesses of the snow cover. Since uncorrected precipitation data will be used in the precipitation analyses, the reported precipitation rates may be somewhat lower than the real rates (Mustonen 1977), but as the analyses will be performed for detecting long-term trends, not seasonal differences, for instance, the use of uncorrected values will not distort the conclusions. The NAO indices were obtained from the National Center for Atmospheric Research (USA). The non-parametric Mann-Kendall trend test was used to test for monotonic trends in the water temperature, air temperature and precipitation time series, and Spearman's rank correlation (r_S) with the Bonferroni correction to analyse associations between water temperature and climate parameters and between climate parameters and the NAO. The analyses were performed with R 2.11.1 and SPSS 17.0 (SPSS, Chicago, Illinois) for Windows.

Results

The water current and temperature results for March 1994 showed that the water was mixed in the uppermost 4 m under the ice, with water temperatures of 0.22–0.25 °C. This corresponds to the long-term average river water temperature

(0.22 °C in 1963–2011) and to the average lake water temperature at a depth of 1 m (0.20 °C in 1963–2010). A temperature of 1 °C was reached in the lake in 1994 only at depths > 13 m.

The water current velocity ranged between 0.5 and 7.7 cm s^{-1} having its maximum values at site 3, close to the water-temperature measurement site at Kaskesniemi (Fig. 1). The water currents at sites 5, 1 and 2 were mainly directed towards the northwest, while those at sites 3 and 4, were directed towards the southeast and south in the layers above 15 m, with a wider direction distribution in the deeper layers. After passing Kaskesniemi, the river water starts to sink, reaching a depth of 15 m at site 4.

A gradual rise over the period 1962–2010 was detected in the average annual water temperature in the epilimnion of Lake Pyhäselkä during the summer stagnation, whereas during the winter stagnation the average annual water temperature in the top layer showed a decrease from 0.6 °C to 0.2 °C over the 49 years. These trends were site-specific phenomena, being statistically significant at three sites, Noljakansaaret, Kaskesniemi and Pyhäsaari, but not at the deepest site Kokonluoto (Table 1). At the same time (1962–2010), the average temperatures in the bottom layer showed no prolonged trends, neither in summer nor in winter (Table 1). The number of measurements taken per site had no effect on the trends in water temperature. In other words, the years when more measurements were taken, were no "warmer" or "colder" than the years when fewer measurements were taken.

The highest values of Schmidt stability in winter were found for Noljakansaaret (Fig. 3), the temperature measurement site located closest to the river mouth. Stability at this site also seemed to be on the increase from the mid-1970s onwards, whereas no such trend was detected at Kokonluoto, located ca. 15 km south of the river mouth (Fig. 3). In the 1980s, when lake stability values in general were low (Fig. 3), air temperature was also lower than the average for the monitoring period (1933–2010), both in winter and in summer.

The winter (February–March) heat flux from Pielisjoki into Lake Pyhäselkä showed a monotonic decrease over the period 1963–2011 (Mann-Kendall: $\tau = -0.226$, $p = 0.034$) if two three-

Table 1. Mean ± SD water temperature in the top (1–10 m) and bottom layers (≥ 15 m) and their long-term trends (1962–2010) at four sites in Lake Pyhäselkä (Fig. 1). The numbers of measurements (*n*) as well as the trend analysis results (Mann-Kendall τ and *p*) are also shown.

	Summer $T_{1–10\ m}$				Summer $T_{\geq 15\ m}$				Winter $T_{1–10\ m}$				Winter $T_{\geq 15\ m}$			
	mean ± SD	*n*	τ	*p*	mean ± SD	*n*	τ	*p*	mean ± SD	*n*	τ	*p*	mean ± SD	*n*	τ	*p*
Noljakansaaret	16.7 ± 2.32	334	0.423	< 0.001	Max depth 13 m				0.48 ± 0.40	329	−0.541	< 0.001	Max depth 13 m			
Kaskesniemi	17.2 ± 1.76	324	0.366	0.002	12.0 ± 1.95	467	0.081	0.432	0.29 ± 0.19	240	−0.430	< 0.001	1.82 ± 0.56	423	−0.115	0.251
Pyhäsaari	17.1 ± 1.52	316	0.412	< 0.001	11.2 ± 1.56	588	−0.129	0.221	0.30 ± 0.20	227	−0.334	0.015	1.70 ± 0.52	488	0.041	0.706
Kokonluoto	16.9 ± 1.56	235	0.194	0.268	11.9 ± 1.34	627	0.057	0.592	0.41 ± 0.22	223	−0.100	0.328	1.53 ± 0.46	658	−0.095	0.346

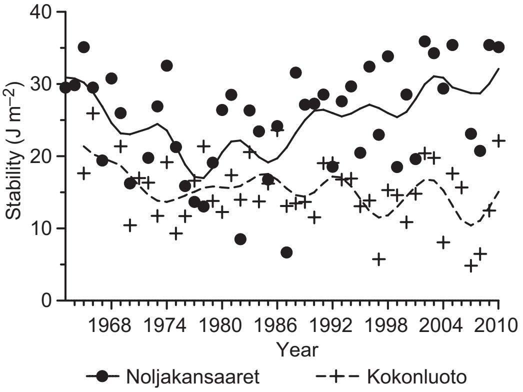

Fig. 3. Winter (January–March) Schmidt stability at (**A**) the shallowest sampling site, located close to the river mouth at Noljakansaaret, and (**B**) the deepest site, ca. 15 km south of the river mouth at Kokonluoto, in 1963–2010. The lines represent a 3rd order moving average.

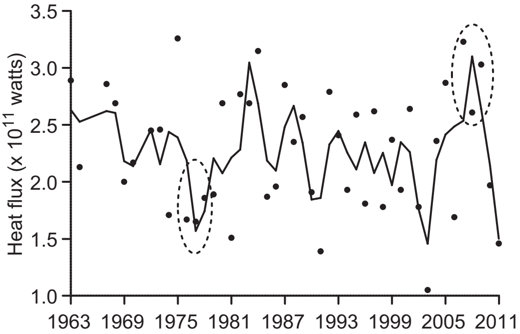

Fig. 4. Winter (February–March) heat-flux from the Pielisjoki to Lake Pyhäselkä in 1963–2011. The line represents a 3rd order moving average. The two three-year periods excluded from the trend analysis because they differed greatly from the preceding and following years (1976–1978 and 2007–2009) are indicated with circles.

year periods (1976–1978 and 2007–2009) were excluded from the data (Fig. 4). During the first of these exceptional periods (1976–1978), the river heat flux was lower than expected on the basis of the preceding and subsequent years, and during the second period (2007–2009) it was higher. It is probable that the latter anomaly may at least be related to weather conditions. The average snow cover in the Lake Pyhäselkä area in 2007–2009 was very thin (21 cm), less than half of the average for the entire monitoring period (45 cm), indicating that much of the precipitation had fallen as rain, not snow, since the average precipitation in January–April in 2007–2009 (39 mm month^{-1}) corresponded to the average for the entire period (36 mm month^{-1}).

It is possible to approximate the wintertime retention of the river water in the shallow northern part of Lake Pyhäselkä by using the mean wintertime discharge of the Pielisjoki (202 m^3 s^{-1} in 1963–2011) and the volume of the uppermost 5 m layer in the area (70 km^2), which includes the sampling sites of Noljakansaaret and Kaskesniemi and the water current measurements points 1, 2, 3 and 5 (Fig. 1). The calculations result in a retention time of 20 days and signify that the lake water is totally displaced by the river input in this northern part. The retention time for the entire lake with a mean outflow is 3.5 months.

The average annual air temperature during the monitoring period from 1933 to 2010, calculated from the monthly average temperatures in the area (mean = 2.7 °C, range = –0.2 to 4.9 °C) did not show a clear increase or decrease (Mann-Kendall: $\tau = 0.024$, $p = 0.761$) (Fig. 5), and the same was true for precipitation — for which no monotonic trends were detected, neither in winter (January–April: mean = 36 mm month^{-1}, range = 21–64 mm month^{-1}) nor in summer (June–August: mean = 71 mm month^{-1}, range = 12–146 mm month^{-1}) ($\tau = 0.021$, $p = 0.792$ and $\tau = 0.033$, $p = 0.676$, respectively), and also for snow cover thickness (mean = 45 cm, range = 14–82 cm) ($\tau = 0.058$, $p = 0.465$).

The only correlation among the annual average air temperature, precipitation, NAO index, epilimnetic water temperature and hypolimnetic water temperature in summer (June–August) in 1962–2010 was between epilimnetic water temperature and air temperature ($r_S = 0.452$, Bonferroni adjusted $p = 0.010$, $n = 49$), whereas in winter (January–April), both the annual average air temperature and precipitation correlated positively with the NAO index ($r_S = 0.618$, Bonferroni adjusted $p < 0.01$, $n = 49$ and $r_S = 0.463$, Bonferroni adjusted $p = 0.010$, $n = 49$, respectively). Water temperature did not correlate with the climatic variables in winter.

Discussion

The present results emphasize the need for taking local phenomena into account when drawing

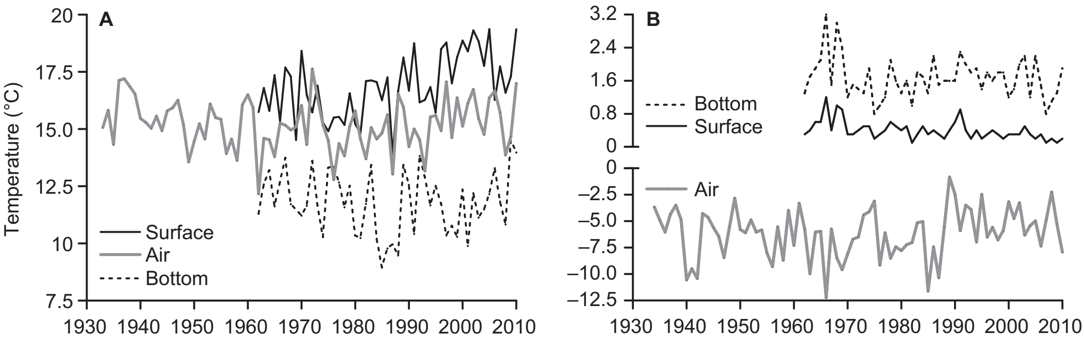

Fig. 5. Trends in water temperature in Lake Pyhäselkä and regional air temperatures in (**A**) summer (June–August) and (**B**) winter (January–April). Surface and bottom refer to the uppermost (0–10 m) and lowermost (≤ 15 m) water layers, respectively. The *x*-axes indicate year (1931–2010).

conclusions about the effects of climate change on lakes. Lake-specific factors such as the inflow from rivers, and the timing of ice formation and melting may alter a lake's response to climate and thus hinder the detection of climatic effects. Climatic variability and change are external drivers of lake dynamics, but individual lake ecosystems filter these signals and alter their expression in different ways (Magnuson *et al*. 2004). The construction of generalizations and predictions regarding the impact of the changing climate on boreal lakes is a highly challenging task due to differences in temporal coherence between limnological variables, particularly under the ice (Järvinen *et al*. 2002), and the complex thermal dynamics of these lakes. Besides, the impact of climate on a lake can be stronger than expected solely on the basis of meteorological parameters (Magnuson *et al*. 2000, Hyvärinen 2003). In Lake Pyhäselkä, for instance, summertime epilimnetic water temperatures followed the general trends in air temperature, which was actually very much the outcome that could be expected (cf. Hurrell *et al*. 2003). The amount of solar radiation reaching the Earth's surface has increased since the 1990s (Pinker *et al*. 2005, Wild *et al*. 2005), which has resulted in heating both land and water. Moreover, water of Lake Pyhäselkä has become darker during the early years of the new millennium (Voutilainen and Huuskonen 2010), which has affected its ability to absorb radiation (Huovinen *et al*. 2003) and accumulate energy. On the other hand, it is hard to say on the basis of the present data whether the air temperature in the area is really increasing in the long run, since the average summertime (June–August) air temperature in the 1930s was just as high as it is nowadays (Fig. 5).

By contrast with the summer water temperatures, the wintertime water temperatures in the top layer of Lake Pyhäselkä tended to decrease during the period studied here. In their simulation of the impacts of climate change on the thermodynamics of Finnish lakes, Saloranta *et al*. (2009) found a negative correlation between air and water temperatures in winter and early spring, when the lakes are covered by ice, while Blenckner and Chen (2003), relating several hydrological lake variables to indices representing atmospheric circulation, found winter water temperatures to be the only variable not correlating with the atmospheric circulation. These authors explained the simulated (Saloranta *et al*. 2009) and measured (Blenckner and Chen 2003) "winter anomaly" as a consequence of thermal buffering by the lake ice and snow cover. In the case of Lake Pyhäselkä, it seems that the river inflow plays a significant role in the process which causes a decrease in lake water temperature.

Our results revealed that water from the Pielisjoki forms a few-metre-thick layer that flows below the lake ice and creates an anticlockwise circulation due to the Coriolis effect caused by Earth's rotation (cf. Carmack *et al*. 1979), while at the same time following the morphometric deformations present in Lake Pyhäselkä. The uppermost six to seven metres of the northernmost part of the lake, beyond a line between the river mouth and Kaskesniemi

(Fig. 1), appears to be "filled" with water from the Pielisjoki during the ice-covered period, and the heat flow associated with the river water has a considerable effect on the wintertime heat budget of the lake, when solar and atmospheric radiation is eliminated by the snow and ice cover. A similar lake–river interaction has been noted in British Columbia, where the large Thompson River has been shown to cool the deep intermontane Kamloops Lake in wintertime (Carmack 1978, Carmack *et al.* 1979), although in this case the lake is not covered by ice in winter. We suggest that the decrease in heat flux from the Pielisjoki detected is due to the climate change, although we also acknowledge the urgent need for studying the possible effects of hydropower production on the river flow. It has been demonstrated by several authors (Huttula *et al.* 1992, Elo *et al.* 1998) that climate change will extend the ice-free periods in lakes and rivers, increasing the frequency of frazil ice jams in rivers and effecting a cooling of the river water (Huokuna *et al.* 2009, Aaltonen *et al.* 2010). In general, the ongoing climate change is expected to increase precipitation and runoff in northern Europe (Arnell 1999), but not necessarily to increase average snow depth, as less of the precipitation will fall as snow in winter (Barnett *et al.* 2005). The decrease in heat flux from the Pielisjoki will means that less thermal energy will pass from the river to Lake Pyhäselkä. The diverging trends in Schmidt stability between the sampling site located close to the river mouth at Noljakansaaret and that located ca. 15 km south of the river mouth at Kokonluoto support our conclusion that the cooling of the lake during winter is due to water from the river. In this case, the fact that the sampling site located close to the river mouth shows a strong inverse thermal stratification in wintertime despite its shallowness is of particular importance (Fig. 3). It may well be that both findings, the temperature trend and the inverse stratification, are the results of cold water flowing in from the Pielisjoki.

Interestingly, the trends in water temperature (an increase in summer and a decrease in winter) did not hold good at one of the sampling sites, Kokonluoto, which is situated in the deep abyssal area of Lake Pyhäselkä (Fig. 1). This is most likely related to the water depth at the site (nearly 70 m) and wind-induced water currents in the lake. The main direction of flow of the water from the Pielisjoki in Lake Pyhäselkä, both in winter (this study) and summer (Huttula *et al.* 1996), is northwards from the river mouth, turning back southwards at the north end of the lake. Thus the flow caused by the river discharge affects mainly the northern part of the lake, where the Noljakansaaret and Kaskesniemi sampling sites are situated (Fig. 1). At the southernmost sampling site, Kokonluoto, epilimnetic water currents in summer are induced mainly by wind and not by the river flow (Huttula *et al.* 1996). Consequently, as the prevailing summer winds from the south and southwest move the warm surface waters towards the north end of the lake, as shown by Huttula *et al.* (1996), the compensational water will very probably be collected from the deep, cool water near Kokonluoto, which will induce vertical mixing and upwelling and thus hide any effects of more general phenomena on water temperature. It may indeed be speculated that, if the decrease in water temperature in Lake Pyhäselkä in winter were a result of changing weather conditions in autumn, when the lake freezes over, the trend would not be stronger near the river mouth as has been seen to be the case. Besides, no trend towards a later date of freezing over in the Scandinavian lakes has been observed in the past decades (Blenckner *et al.* 2004)

Several hypotheses arising from the present results need to be tested in the near future, and we suggest that special attention should be paid to the following questions: (1) how climate change affects the seasonal thermal stratification in dimictic boreal lakes, (2) how the changing temperature profile affects oxygen conditions near the lake bottom, and (3) whether the trend towards a wintertime decrease in water temperatures might be a large-scale phenomenon affecting ice-covered lakes. Intensive data collection campaigns and 3D modelling will probably be needed to solve the problems of wintertime river water advection and local mixing processes in summer. For this purpose, careful attention should be paid to the modelling of ice dynamics and vertical mixing processes. Although the present analyses and conclusions are based solely on data from the Lake Pyhäselkä–Pielisjoki waterway system, it seems likely that the patterns described here will also prove applicable to other lake–river systems exhibiting similar morphological and hydrological conditions.

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