Frequency of episodic stratification in the near surface of Lake Opeongo and other small lakes

Patricia Pernica and Mathew Wells

ABSTRACT

Wind-driven mixing in the epilimnion of a deep lake can be suppressed when there is a weak near surface stratification, which occurs frequently during periods of strong solar heating and weak winds. Using data from a vertical chain of fast response thermistors, we analyze the frequency of near surface stratification in the top 2 meters of the epilimnion in Lake Opeongo, Ontario for the periods between May and August in 2009 and 2010. Near surface thermoclines (as defined by $dT/dz > 0.2\,^{\circ}\mathrm{C\,m^{-1}}$ between 1 and 2 m) occur for 24% of the sampling period in 2009, 37% of the sampling period in 2010 and correspond to periods of high values of gradient Richardson number. During daytime the epilimnion is stratified up to 45% of the time. At night, cooling generally leads to a more isothermal profile, but near surface thermoclines still form at least 20% of the time. Extended periods of near surface stratification (>1 h), account for more than 80% of the stratified period. We compare these findings with previous observations from the Experimental Lakes Area in Northern Ontario, and discuss the biological implications of episodic stratification.

Key words | epilimnion, near surface stratification, physical limnology, turbulence

Patricia Pernica (corresponding author)
Department of Physics,
University of Toronto,
60 St George St,
Toronto,
Ontario,
Canada M5S 1A7
E-mail: *ppernica@physics.utoronto.ca*

Mathew Wells
University of Toronto,
1265 Military Trail,
Toronto,
Ontario,
Canada M1C 1A4

INTRODUCTION

The typical thermal structure of a dimictic mid-latitude lake in the summer is usually depicted as a three-layer system: a warm isothermal epilimnion separated from a cool hypolimnion by the seasonal thermocline, a region of high thermal stratification. However, weak temperature gradients can form in the epilimnion from daytime solar heating, so that this layer is not continuously isothermal. These weak temperature gradients are referred to as 'diurnal thermoclines' (Imberger 1985; Monismith & MacIntyre 2009) or 'near-surface thermoclines' (Xenopoulos & Schindler 2001). These near surface thermoclines occur in many shallow polymictic lakes and in some slow moving rivers, which stratify and destratify on a daily basis, (MacIntyre 1993; Condie & Webster 2001; Ford *et al.* 2002). Such episodic stratification can also occur in the epilimnion of deeper lakes which are considered dimictic or monomictic (Imberger 1985; Xenopoulos & Schindler 2001; MacIntyre *et al.* 2010). This study aims to draw attention to the importance of the frequency and duration of these weak temperature gradients.

The presence of weak stratification can suppress turbulent mixing in the surface layer, which can in turn lead to a reduction in fluxes of dissolved gases and changes vertical distribution of nutrients and aquatic organisms. For example, gas transfer coefficients have been shown to be strongly dependent on mixing rates in the epilimnion, decreasing when wind-induced turbulence is damped by epilimnetic stratification (MacIntyre *et al.* 2010). Related work by Ford *et al.* (2002) showed that episodic stratification in a shallow floodplain lake could lead to anoxia in the epilimnetic waters due to high respiratory demands. Huotari *et al.* (2011) also showed that the flux of carbon dioxide out of a small shallow lake in Finland was strongly controlled by the stability of the lake's temperature stratification. They observed that when the depth averaged buoyancy frequency was greater than $0.09\ \mathrm{s^{-1}}$, the measured flux of carbon dioxide was almost zero. The presence of stratification in the epilimnion can also change the depth to which active mixing occurs, resulting in fluctuations in irradiance which

doi: 10.2166/wqrjc.2012.001

in turn can affect photosynthetic rates (MacIntyre 1993). For instance, Bormans *et al*. (1997) showed that the presence of weak stratification was required to form sustained algal blooms in a slow moving river in Southern Australia. Since these effects were due to the non-isothermal state of the epilimnion, the role of episodic epilimnetic stratification must be fully understood in order to properly model these physical, biological, and chemical processes.

These reductions in fluxes observed during periods of weak stratification can be related to a reduction in turbulent mixing, which in lakes is often due to wind-driven forcing (Holloway 1980; Condie & Webster 2001; Branco & Torgersen 2009). Thermal stratification can inhibit mixing if it is large relative to the current velocity shear. Studies have shown that stratification on the order of 1 °C over the depth of an epilimnion can form during periods of low flow velocity and larger heat fluxes (Ackerman *et al*. 2001; Branco & Torgersen 2009). Conditions leading to the formation of weak temperature gradients occur frequently during summer in mid-latitude lakes when air temperatures exceed water temperatures for extended periods. Xenopoulos & Schindler (2001) observed that near surface weak stratification occurred in 39 mid-latitude lakes at least 20% of the time in summer.

One way to parameterize the magnitude of shear-driven mixing is through the gradient Richardson number, Ri_g, defined as:

$$Ri_g = \frac{N^2}{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2} \quad (1)$$

where the buoyancy frequency is defined as: $N = ((g/\rho_o)(\partial\rho/\partial z))^{1/2}$, g is the gravitational constant, ρ is the density of water, and z is the depth measured from the surface. The denominator of Equation (1) is the vertical velocity shear. According to stability analysis (Miles 1961; Monismith & MacIntyre 2009) there will be little to no turbulent mixing for $Ri_g > 0.25$.

While many studies recognize the importance of near surface thermoclines, there does not appear to be a standard definition for these thermoclines. Imberger (1985) and Shay & Gregg (1986) have suggested that a temperature difference of 0.02 °C over 1 m is sufficient for a near surface thermocline to form, while Xenopoulos & Schindler (2001) used a definition of $T_{0m} - T_{1m} \geq 0.2\,^\circ\mathrm{C}$ to identify the presence of diurnal thermoclines. The stratification for an average value of velocity shear producing $Ri_g > 0.25$ can also be used to define a near surface thermocline. Approximating the current velocity shear and using $Ri_g^{\text{crit}} = 0.25$ generates a critical buoyancy frequency and hence a minimum temperature stratification necessary to inhibit mixing. For example, the maximum average wind speeds for lakes in the Experimental Lakes Area (ELA) is approximately $3\ \mathrm{m\,s^{-1}}$ (Xenopoulos & Schindler 2001). Empirical studies have demonstrated a linear relationship between wind speed, W, and surface current speed, U_s, where $U_s/W =$ 1–3% (George 1981). Using this relationship and the 'law of the wall' we can approximate the resulting average velocity gradient as $0.025\ \mathrm{s^{-1}}$. Using Equation (1) this generates a critical density gradient for the suppression of turbulence of $0.016\ \mathrm{kg\,m^{-4}}$. Assuming a surface temperature of 20 °C this corresponds to a temperature gradient of approximately $0.1\ ^\circ\mathrm{C\,m^{-1}}$. For this analysis we used a similar definition to Xenopoulos & Schindler (2001) of $\mathrm{d}T/\mathrm{d}z > 0.2\,^\circ\mathrm{C}$, in order to compare our results with their compiled data set.

In this paper we analyzed high-frequency temperature data taken from a vertical array of fast response thermistors and velocity data from an Acoustic Doppler Current Profiler (ADCP) in the epilimnion of Lake Opeongo. Measurements were made during the summer months (May–August) of 2009 and 2010, when the seasonal thermocline had already formed. Stratification was described in terms of temperature difference and gradient Richardson number, Ri_g. We determined the frequency at which near surface thermoclines form (as defined by $\mathrm{d}T/\mathrm{d}z > 0.2\,^\circ\mathrm{C}$), as well as their duration. We compared our large and high frequency data set with the smaller data set analyzed by Xenopoulos & Schindler (2001). We conclude the article by discussing the biological importance of these weak but frequent near surface thermoclines.

METHODS

The observations were made in Lake Opeongo, Ontario, Canada (N45°42′, W78°22′), a freshwater, oligotrophic, dimictic lake composed of four basins with a total area of

58.6 km^2. This study was conducted in South Arm basin which has a surface area of 22.1 km^2, maximum depth of 51.8 m, mean depth of 15 m, and a maximum fetch of 7.2 km (Figure 1). Concentrations of dissolved organic matter (DOM) were high, resulting in an average diffuse attenuation coefficient (K_d) of 0.85 m^{-1} and the 1% light level occurred between 4 and 5 m (King *et al*. 1999).

Wind speed and direction, air temperature, and relative humidity were measured by a meteorological station located 2 m above the mean lake level (model 05103, R. M. Young) at 30 s intervals and averaged over 10 min. The station was located on a small island (N 45°41′3″, W 78°23′9″) near the center of the South Arm basin (Figure 1(b)). Due to technical problems with the weather station, data in 2009 were only available from day 147 to day 175, day 195 to day 215, and day 220 to day 235, and in 2010 were available from day 149 to day 189 and day 214 to day 236.

The stratification in the lake was recorded using a vertical array of moored thermistors located at N 45°41′34.6″, W 78°23′48.4″ during the periods of May–August 2009 and 2010 (Figure 1). In 2009 the temperature was recorded by a chain of 16 RBR TR-1060 thermistors. Measurements were recorded between a depth of 1 to 12 m, with the loggers spaced 1 m apart in the epilimnion and 50 cm apart throughout the thermocline. The RBR TR-1060 units had a response time of 3 s, were accurate to ±0.002 °C and sampled every 4 s. Temperature data in 2010 were recorded using two chains of thermistors positioned adjacent to one another. A chain of 12 RBR TR-1060 thermistors recorded data every 0.6 m from 1.7 to 8.3 m below the surface from May to July and from 0.6 to 7.2 m from July to August, again sampling every 4 s. A chain of 20 onset HOBO loggers spaced 1 m apart and recording every 5 min were deployed with sensors from 0.1 to 20.1 m for May to July and from 0 to 20.6 m from July to August. These loggers were accurate to ± 0.2 °C and had a response time of 5 min.

Measurements of velocity throughout the water column were collected using a Teledyne RD Instrument (RDI) 600 kHz, Acoustic Doppler Current Profiler (ADCP) moored on the bottom at a depth of 22 m located adjacent to the RBR loggers. The ADCP recorded velocities every 2 s in 2009 and every 4 s in 2010 in bins of 60 cm from 2.3 m below the surface to the bottom. During the 2009 field season we sampled at 0.5 Hz over a 10-minute burst every 30 min. During the 2010 season we sampled continuously.

Values of Ri_g were calculated using Equation (1). The RBR temperature data were averaged over 10 min and

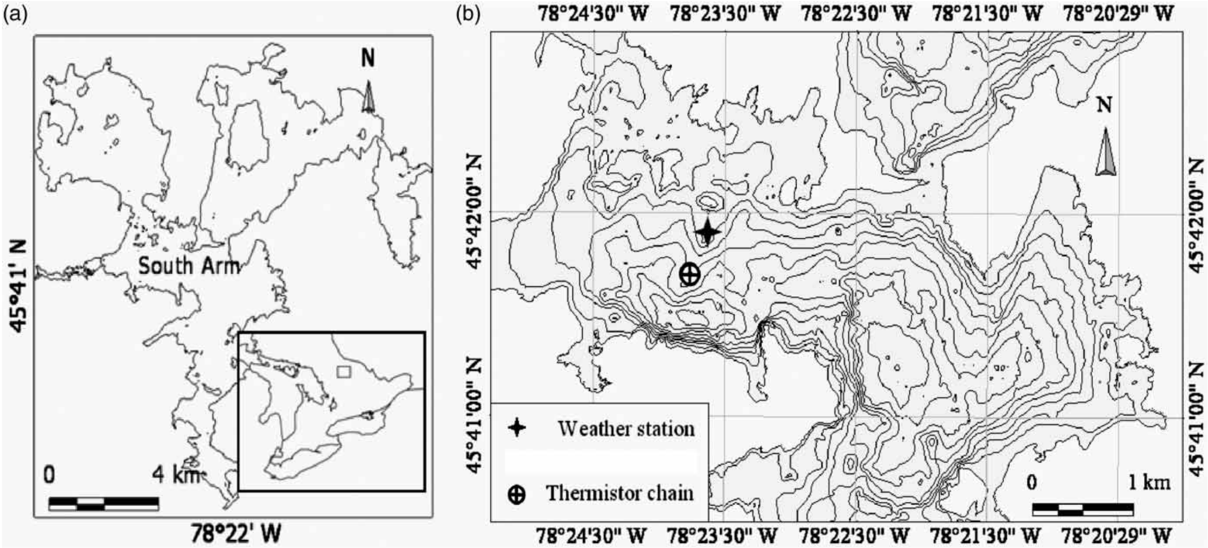

Figure 1 | (a) Map of Lake Opeongo with inset showing location in Ontario and South Arm basin marked. (b) South Arm of Lake Opeongo (with 5 m contours) including the locations of the thermistor chains and weather station.

were depth interpolated to every 0.6 m prior to computing density. Velocity shear was calculated with $\Delta z = 0.6$ m, the size of the velocity depth bins using 10 min averaged velocity data. This produced 10 min averaged values of Ri_g.

Since we did not have a temperature sensor at the surface of the lake, we calculated a near surface thermocline as occurring for $dT/dz > 0.2\,^{\circ}\mathrm{C\,m^{-1}}$ between depths of 1 to 2 m to compare with near surface thermocline data from Xenopoulos & Schindler (2001) defined by $T_{0m} - T_{1m} > 0.2\,^{\circ}\mathrm{C}$. For the 2009 data, this was done by calculating $T_{1m} - T_{2m} > 0.2\,^{\circ}\mathrm{C}$ from a 1 min average of the RBR temperature data. For May to early July 2010 we did not have RBR loggers close enough to the surface to calculate the presence of a near surface thermocline. For mid-July to August 2010 we calculated $dT/dz > 0.2\,^{\circ}\mathrm{C\,m^{-1}}$ using $T_{1.2m} - T_{1.8m} > 0.12\,^{\circ}\mathrm{C}$ from a 1 min average of the RBR temperature data. Differences in the frequency of near surface thermoclines as a function of time of day were also analyzed. For this study, 'daytime' was defined as occurring between the hours of 0800 and 1900 h and 'nighttime' after 1900 h and before 0800 h, in order to make a comparison with the results of Xenopoulos & Schindler (2001).

The depths of the epilimnion and the seasonal thermocline were defined in terms of observed temperature gradient. Using the temperature data from the 16 RBR loggers in 2009 and the 20 HOBO loggers in 2010, we established the location of the seasonal thermocline as the position of the maximum density gradient. We defined this position as being halfway between the two adjacent loggers that encompassed the region of greatest change in density. This procedure is similar to the method outlined by Read *et al.* (2011) where they used a more refined procedure of weighting adjacent density gradient calculations to locate the maximum change in density. Read *et al.* (2011) defined the depth of the epilimnion based on a density gradient cutoff defined for a particular system. We defined the epilimnion as extending down from the surface to a depth where the buoyancy frequency is equivalent to 65% of the buoyancy frequency at the thermocline (the location of maximum buoyancy frequency). Functionally, this is similar to Read *et al.* (2011) as we essentially defined a cutoff density gradient. The metalimnion region was defined as the thickness of the thermocline extending from the base of the epilimnion to the top of the hypolimnion encompassing the region of strongest vertical stratification.

RESULTS

The meteorological, temperature, and velocity data for both years are compared in the following section. Further analysis of these data, including calculating buoyancy frequency, gradient Richardson number (Ri_g), and frequency and duration of near surface thermoclines, is also included.

Meteorological conditions were broadly similar for 2009 and 2010 allowing for some generalizations. Wind speed, air temperature, and relative humidity data for August 2009 and 2010 are shown in Figure 2. These lake data varied over diel timescales with greater wind speeds, air temperatures, and lower relative humidity occurring in the afternoons. Wind speed and relative humidity displayed no significant difference between August 2009 and August 2010. Average wind speed in 2009 was $3.26\ \mathrm{m\,s^{-1}}$ as compared to $3.37\ \mathrm{m\,s^{-1}}$ in 2010, both of which are comparable to long-term averages described in King *et al.* (1999). Relative humidity was generally less than 50% during the afternoon and increased to >80% overnight for both years. Air temperatures were slightly higher in 2010 with an average in August of 20.5 °C as compared to 19.2 °C in 2009. Monthly averages of air temperature data from the Environment Canada meteorological station at the Algonquin Park East Gate (located 30 km from the lake) for May–August of the past 6 years (2005–2010) were used for comparison. May–July 2009 were approximately 1 °C cooler than the 6 year average, while July and August 2010 were approximately 1 °C warmer than the 6 year average. Thus the results from the 2009 and 2010 field seasons are broadly consistent with typical conditions of Lake Opeongo. Temperature difference between the two loggers closest to the surface was generally less than 1 °C except during extended periods of low wind and solar heating which occurred in mid-August for both years (Figure 2(d)). Wind direction was predominately from the west with average direction of 256° (Figure 3).

The seasonal development of stratification for both years was largely similar to the recorded historical data. Average water temperature in the epilimnion for July and

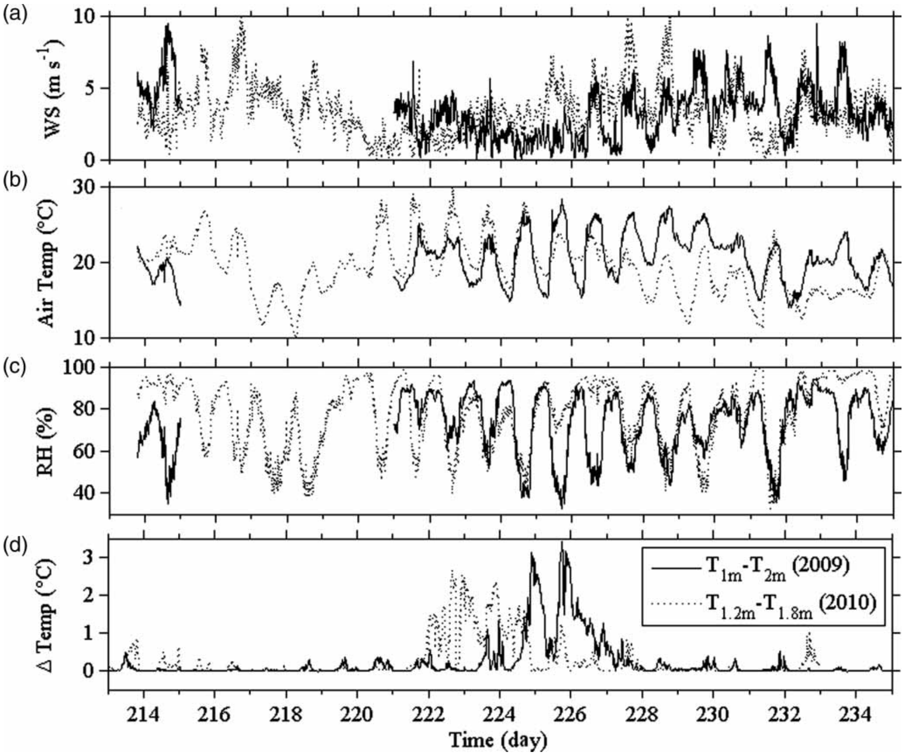

Figure 2 | Ten-minute averaged meteorological data for August 2009 (black) and August 2010 (grey) where: (a) wind speed (m s^{-1}), (b) air temperature (°C), (c) relative humidity (%), and (d) the temperature difference between adjacent loggers near the surface.

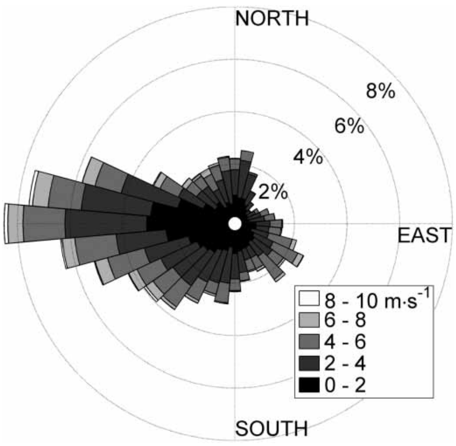

Figure 3 | Wind speed and direction measured on an island in Lake Opeongo during the summer period of 2009. The seasonal average wind direction was from the west (256°).

August 2009 was 20 °C (standard deviation = 1.4 °C), comparable to the 1958–1994 long-term average of 20.7 °C (King *et al.* 1999). Average water temperature in the epilimnion for the same time period in 2010 was more than 2 °C warmer at 22.1 °C (standard deviation = 0.9 °C). The seasonal thermocline developed mid-June (day 167) in 2009, and was at an average depth of 8 m for the July and August summer period (Figure 4). In 2010 the thermocline developed significantly earlier, around the end of May (day 140) and was substantially shallower at an average depth of 6.8 m for July and August. Both 2009 and 2010 experienced thermoclines that were significantly shallower than the 1958–1994 average of 9.6 m (King *et al.* 1999; Coman & Wells 2012a, b), which could be due in part to warmer average air temperatures than the average of 17.2 °C for the 1958–1994 period recorded by the Madawaska weather station (N 45°30′, W 78°22′). In general, years with warmer mid-summer air temperatures have shallower thermoclines in Lake Opeongo (King *et al.* 1999). Average epilimnion depth in 2009 was correspondingly deeper at 6.5 m than in 2010 which had an average depth of 5 m.

Average buoyancy frequency during July and August 2009 in the epilimnion and thermocline were 0.0175 and 0.045 s^{-1}, respectively, which for the average epilimnion

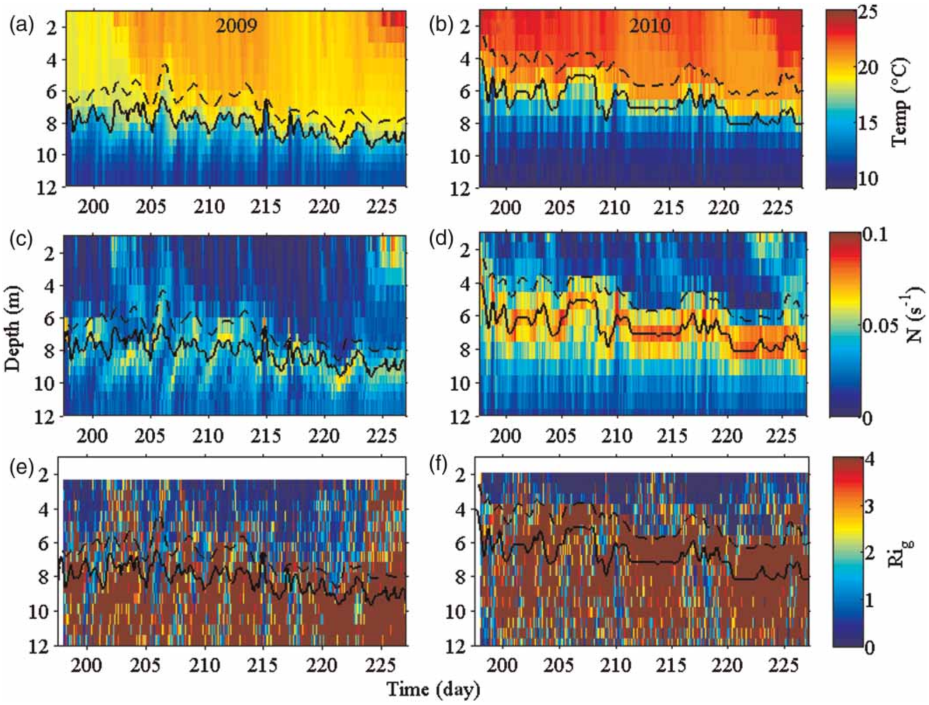

Figure 4 | The evolution of the temperature profile for August 2009 and August 2010 is shown in panels (a) and (b); panels (c) and (d) show the corresponding buoyancy frequency, and panels (e) and (f) show values of Ri_g. The position of the thermocline is marked by the solid black line, while the lower boundary of the epilimnion is marked with the dashed line.

temperatures correspond to temperature gradients of 0.13 and $1.3\,^{\circ}\mathrm{C\,m^{-1}}$. Average buoyancy frequencies in the summer of 2010 were substantially larger within the epilimnion and the thermocline at 0.0243 and $0.064\,\mathrm{s^{-1}}$, respectively, corresponding to temperature gradients of 0.27 and $2.3\,^{\circ}\mathrm{C\,m^{-1}}$, almost twice the 2009 thermal stratification (Figure 4).

To infer the state of mixing in the epilimnion Ri_g was calculated for both years. Values of Ri_g in the epilimnion were slightly lower for 2009 than 2010 which is consistent with lower average value of N for 2009. The mean values within the epilimnion for late July and August 2009 were high, with $Ri_g = 8$ and $Ri_g = 18$ for 2010 (Figure 4). For both years values of $Ri_g < 0.25$ within the epilimnion occurred approximately 30% of the time. The high average values of Ri_g suggest that for a significant period of both summers, the thermal stratification was strong enough to overcome the current shear in order to prevent mixing. During periods of cooling or increased winds (i.e., day 214–218 for 2009 and day 216–220 for 2010) mean values dropped to $Ri_g \sim 1$. Conversely, during periods of low winds and high heating (day 224–226 for 2009 and day 202–204 for 2010) mean values in the epilimnion exceeded 20.

Using the definition of $\mathrm{d}T/\mathrm{d}z > 0.2\,^{\circ}\mathrm{C\,m^{-1}}$, near surface thermoclines occurred for 24% of the sampling period in 2009 and 37% of the sampling period in 2010. This result is consistent with frequent values of large values of Ri_g. For both years the percentage of near surface thermoclines was slightly higher during the day than at night due to daytime heating (Table 1). Near surface thermoclines were also more frequent early in the season (May–June). During 2009, May–June daytime near surface thermoclines occurred 37% of the time.

Table 1 | Frequency of near surface thermoclines in South Arm basin for 2009 and 2010 as a function of time of day and season

Near surface thermoclines	2009	2010
Average frequency	24%	37%
Average night-time frequency	20%	27%
Average daytime frequency	31%	45%
Average frequency May–June	30%	N/A
Average frequency July–August	19%	31%

Once formed, near surface thermoclines were persistent features of the epilimnetic waters of Lake Opeongo. Stratified periods of less than 30 min accounted for approximately 10% of the stratification record while extended periods of stratification (>1 h) represented the majority of the total stratification period. During the July and August summer period, only 5–8% of near surface thermoclines remained for less than 10 min. During July and August 2009, near surface thermoclines were present 20% of the time and for that period, 80% of that time the stratification persisted for more than 1 h. Similarly, in July and August 2010, near surface thermoclines occurred for 31% of the record and of that period, 87% of that time the stratification persisted for longer than 1 h (Figure 5). During both summers there was at least one instance of the near surface thermocline persisting for more than 2 days.

DISCUSSION

Our major observation is that near surface thermoclines occurred frequently in the South Arm basin of Lake Opeongo. Our observations were also consistent with those made by Xenopoulos & Schindler (2001) in 39 lakes of the ELA in Ontario, Canada. When comparing the 2009 and 2010 near surface thermocline data with the data reported by Xenopoulos & Schindler (2001) it is important to note a few important details. First, we have defined the near surface thermocline as occurring between 1 and 2 m rather than 0 and 1 m due to the placement of our loggers. We have, however, compared the occurrence of the same gradient of 0.2 °C m^{-1}. We also present results from a long time series data set over 2 years taken in one location (South Arm basin, Lake Opeongo) as compared with 25 years of weekly and bi-weekly profiles from 39 lakes. Functionally we have more than five million profiles from one lake that we compare with 3,344 profiles from 39 lakes. Hence we are able to determine the duration of near surface thermoclines and with our much larger data set, we have a more complete representation of near surface stratification during the summer period.

The average frequency at which near surface thermoclines developed is plotted as a function of lake size and light attenuation coefficient and compared with data from Xenopoulos & Schindler (2001) in Figures 6 and 7. Daytime frequency (+) of the near surface thermocline as a function of lake size (Figure 6) is well predicted by the empirical curve (equation in Figure 1 of Xenopoulos & Schindler 2001); however, both total frequency (*) and night frequency (x) are significantly less than predicted by the empirical curve. This is not unexpected as profiles used to generate the empirical curve were taken at 0800 and 1200 h, which are times that occurred in our daytime sampling. This could also be in part due to our definition of near surface thermoclines as occurring deeper in the water column than the definition presented by Xenopoulos & Schindler

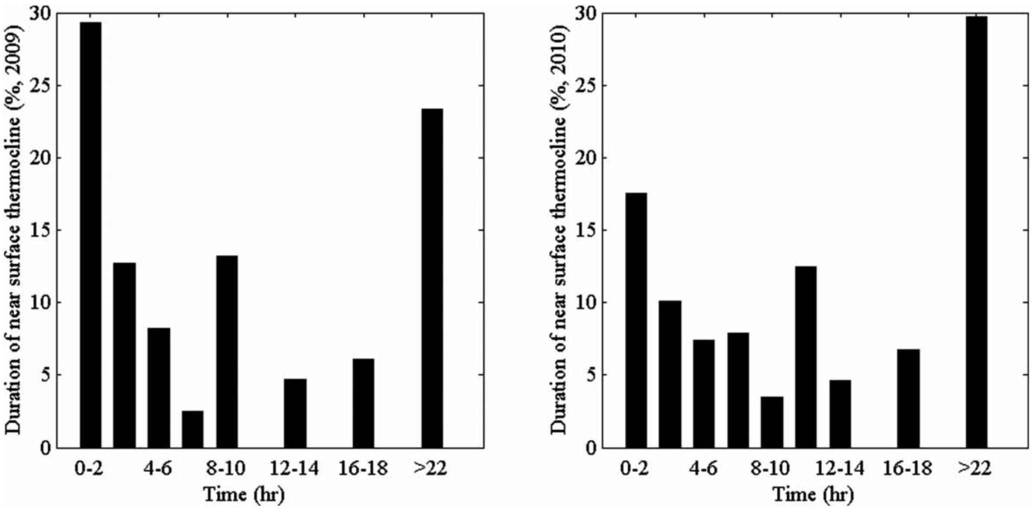

Figure 5 | Duration of near surface thermoclines for July and August 2009 and 2010 as a percentage of total near surface thermocline period.

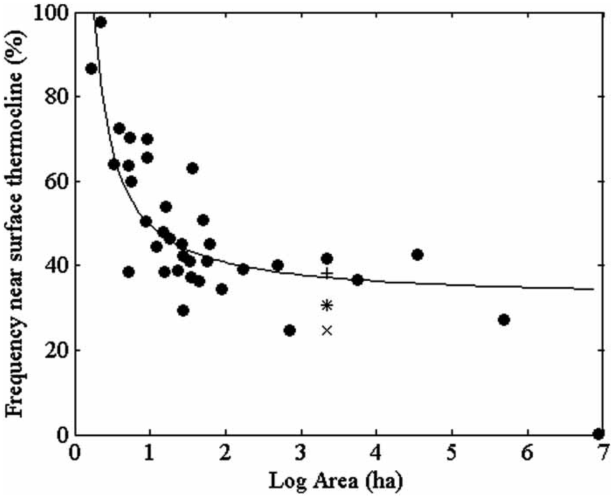

Figure 6 | Frequency of near surface thermoclines as a function of area for a range of lakes (•) (Xenopoulos & Schindler 2001) compared with total $dT/dz > 0.2\ ^\circ C\ m^{-1}$ (*), daytime (+) and night-time (x) data from Lake Opeongo in 2009 and 2010.

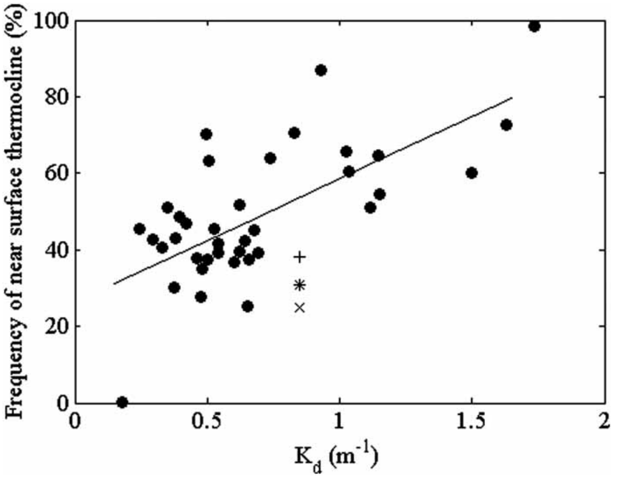

Figure 7 | Frequency of near surface thermoclines as a function of light extinction coefficient (K_d) for a range of lakes (•) (Xenopoulos & Schindler 2001) compared with total $dT/dz > 0.2\ ^\circ C\ m^{-1}$ (*), daytime (+) and night-time (x) data from Lake Opeongo in 2009 and 2010.

(2001). Solar heating would have a greater effect closer to the surface generating more frequent stratification. If $T_{0.6m}$–$T_{1.2m} > 0.12\ ^\circ C$ from the 2010 data is used to define a near surface thermocline, frequency of occurrence increases to 80% for July and August.

Frequency of near surface thermoclines as a function of light extinction coefficient, K_d is overpredicted by the empirical curve even for daytime profiles (Figure 7). The differences could in part be due to our deeper definition of near surface thermoclines. There is also a correlation between K_d and seasonal thermocline depth, with deeper thermoclines occurring for smaller values of K_d since for clear-water lakes solar radiation penetrates further (Xenopoulos & Schindler 2001); however, the influence of K_d on thermocline depth diminishes as lake size increases above 500 ha (Fee *et al.* 1996; King *et al.* 1999). A similar reduced correlation of K_d and near surface thermoclines for larger lakes could also be possible, as the frequency of near surface thermoclines is overpredicted for both Lake Nippigon and Lake Linge, which have surface areas greater than 700 ha (Xenopoulos & Schindler 2001).

The comparison in Figure 8 of our measurements of buoyancy frequency, N, as a function of lake size suggests a significant underprediction by extrapolating the empirical fit suggested by Xenopoulos & Schindler (2001) to the larger area of 2,200 ha of the south arm of Lake Opeongo. Following the trend of the empirical fit would suggest a value of N less than zero for lakes larger than 800 ha which would not be consistent with near surface thermoclines occurring 20–30% of the time in larger lakes. Since the buoyancy frequency data in Xenopoulos & Schindler (2001) was presented for smaller ELA lakes only, it is likely that the inclusion of larger lakes would have demonstrated an asymptotic trend at a value larger than zero.

Our definition of near surface thermocline of $dT/dz > 0.2\ ^\circ C\ m^{-1}$ was chosen in order to compare our data with

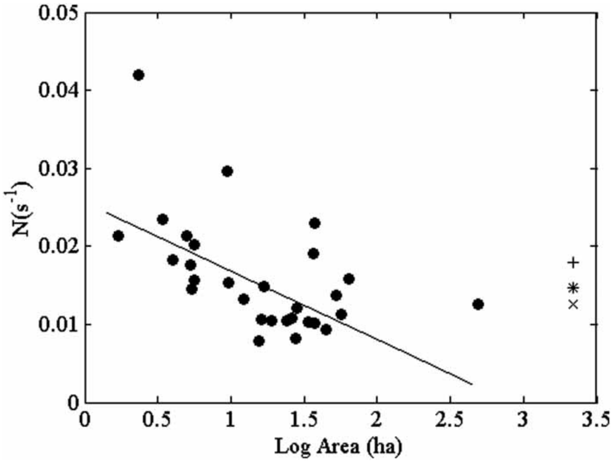

Figure 8 | Buoyancy frequency in the top 1–2 m of the water column as a function of lake area for a range of lakes (•) (Xenopoulos & Schindler 2001) compared with total buoyancy frequency (*), daytime (+) and night-time (x) data from Lake Opeongo in 2009 and 2010.

those from Xenopoulos & Schindler (2001). However, analyzing the Ri_g data suggests that this definition may be somewhat conservative. Using $Ri_g{}^{\text{crit}} = 0.25$ as when thermal stratification impedes shear-driven mixing we approximated the near surface thermocline that could inhibit turbulent mixing. From the velocity data for Lake Opeongo, the average shear between 2 and 3 m was 0.03 s^{-1}. Using $Ri_g = 0.25$ and Equation (1), we calculated a critical $N^2 = 2.25 \times 10^{-4}$ s^{-2}. Assuming a temperature at that depth of 22 °C, this analysis generated a temperature gradient of 0.1 °C m^{-1} required to impede turbulent mixing. However, this brief analysis was for deeper in the water column and potential faster velocities near the surface could require a larger stratification to inhibit mixing.

While the frequency of occurrence of near surface thermoclines is important in understanding the dynamics in the upper water column, the duration of these events is especially important for planktonic organisms. The magnitude of vertical mixing is related to the value of Ri_g, with low values indicating high values of mixing and large values of Ri_g indicating high relative values of temperature stratification and little mixing. Therefore, long periods of near surface stratification will result in long periods where shear-driven mixing is greatly reduced. These periods occur mainly during periods of low winds and strong solar heating. Since at least 80% of near surface stratification persisted for longer than 1 h these extended periods of low turbulent mixing can have implications for the distribution of plankton and other aquatic organisms (Imberger 1985; MacIntyre 1993). Turbulent mixing can inhibit negatively buoyant phytoplankton from settling out of the mixed layer, therefore, the formation and duration of near surface thermoclines can drastically change the time that phytoplankton persist near the surface (Reynolds 1984). These organisms that may be trapped near the surface by near surface thermoclines can be subject to high solar irradiance which can inhibit growth (Vincent *et al.* 1984; Xenopoulos & Schindler 2001). The extended duration of near surface stratifications can also suppress the transfer of gases through the water column, as discussed by Ford *et al.* (2002) MacIntyre *et al.* (2010), and Huotari *et al.* (2011).

An important implication of our observations of a persistent near surface thermocline is that empirical estimates of mixed layer thickness (such as Fee *et al.* 1996) should be carefully interpreted. For instance the data in Figure 4 of Fee *et al.* (1996) suggest that the mean midsummer mixing depth E_d of lakes in the Canadian shield in Ontario is well approximated by $E_d = 2.92 + 0.0607\ A_o{}^{0.25}$, where E_d is the depth in m and A_o is the surface area of the lake in m^2. The south arm of Lake Opeongo has an area of 22 km^2, so this formula predicts that the mixed layer depth is 7 m, very close to the 5–6 m depth of the epilimnion shown in Figure 3. While this empirical formula predicts the depth of the mixed layer very well, we have clearly shown that the epilimnion of Lake Opeongo is not an '*essentially isothermal, surface layer*' as described in the opening sentence of Fee *et al.* (1996). Rather the epilimnion has a persistent (albeit weak) near surface thermocline for at least 24% of the summer months that could potentially minimize any turbulence within the surface layer for extended periods. The constant changes in stratification in the epilimnion of Lake Opeongo are very similar to the daily changes that occur in stratification in shallow lakes that are continuously polymictic. Such lakes are defined as 'warm polymictic' near the equator and 'cold polymictic' at high latitudes (Lewis 1983). In both cases one of the common features of these continuously polymictic lakes is that they have shallow depths, less than 5 m, i.e., similar to the depth of the epilimnion in Lake Opeongo. Thus rather than thinking of the epilimnion as an essentially isothermal layer, a better analogy might be to the shallow continuously polymictic lakes where the stratification is weak but constantly changing.

CONCLUSION

The presence of weak thermal stratification in the epilimnetic waters of lakes has strong implications for chemistry gradients, algal physiology, and species diversity as the phytoplankton respond to changing mixing dynamics in the lake. We find that the epilimnion of Lake Opeongo during the summer season is frequently (~30%) stratified, particularly in daylight periods early in the season (~40%). Extended periods of stratification were observed with 80% of the stratified period consisting of near surface thermoclines that persisted for at least 1 h. These events lasted for a significant fraction of the daylight hours, so during these periods the water in the epilimnion was not well mixed, and turbulence as parameterized by Ri_g was of a highly intermittent nature.

The reduction of active vertical turbulence due to weak temperature gradients is known to have implications for the distribution of plankton and other aquatic organisms (Imberger 1985; MacIntyre 1993). The presence of persistent epilimnetic stratification can influence the taxonomic distribution of phytoplankton in a lake, as some species are well adapted to stratified systems while others are better suited to more homogenous areas (Watson *et al.* 1997). Negatively buoyant phytoplankton can settle out of the epilimnion in the absence of turbulence (Reynolds 1984), so the formation and destruction of even a $0.2\,^{\circ}\mathrm{C\,m^{-1}}$ temperature stratification can drastically change the duration that phytoplankton persist in the epilimnion, where light levels are high. Similarly, positively buoyant planktonic organisms could be trapped near the surface by this weak stratification. In this case they would experience high solar irradiance including UVB, which can reduce the growth rates (Vincent *et al.* 1984; Xenopoulos & Schindler 2001). Conversely, in the absence of stratification strong winds can drive high rates of turbulent mixing in the epilimnion which can lead to greater photosynthetic performance of non-motile phytoplankton (Lewis *et al.* 1984).

We hope that the observations of persistent temperature gradients in the epilimnion of Lake Opeongo will spur aquatic biologists to make routine measurements of stratification in surface waters. Many temperature probes that are routinely used only record temperature to an accuracy of $\pm 0.1\,^{\circ}\mathrm{C}$. Hence, to accurately determine the presence of a 0.1 or $0.2\,^{\circ}\mathrm{C\,m^{-1}}$ temperature gradient requires a higher accuracy of at least $\pm 0.01\,^{\circ}\mathrm{C}$. This accuracy is routinely attained by many instruments (such as a CTD (Conductivity, Temperature, Depth)) that are used by oceanographers to measure weak thermal gradients at sea. We suggest that aquatic biologists consider using these more accurate temperature loggers in future studies looking at the spatial distribution of plankton in the euphotic zones of a lake, that typically lie within a lake's epilimnion. By accurately measuring these weak near surface stratifications, aquatic biologists will be able to predict whether the surface waters of the lake are homogeneously mixed, and so determine sensible strategies for the sampling of chemistry and planktonic organisms.

ACKNOWLEDGEMENTS

The fieldwork was made possible by the logistical and financial support of Mark Ridgway and the staff at the Ontario Ministry of Natural Resources' Harkness field station in the Algonquin Park. Wells received funding from the Natural Sciences and Engineering Research Council, the Canadian Foundation for Innovation and the Ontario Ministry of Research and Innovation. Pernica received support from an OGSTT and travel funds from the Centre for Global Change Science at the University of Toronto.

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First received 9 January 2012; accepted in revised form 10 October 2012