Hypoxia and turnover in a small ice-covered temperate lake

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During summer, temperate lakes often exhibit recurrent eutrophication and hypoxia and there has been significant research into the causes and effects. Phytoplankton blooms and low oxygen have also been observed in these lakes under winter ice; however, detailed studies coupling winter stratification to biogeochemistry are lacking. In this study, four years of continuous high-resolution temperature and dissolved oxygen observations are analyzed from a small temperate lake in Ontario, Canada. The lake exhibits near-bed hypoxia and anoxia 2/3 and 1/3 of the time, respectively, and so a low oxygen concentration state should be considered typical for the lake. The watercolumn resets to atmospheric oxygen levels only during fall turnover (63-79 d) and long spring turnover (17-19 d) events. Short spring turnover events (1-8 d), which occur during anomalously warm and calm weather conditions, have uniform temperature profiles, through direct heating of the entire watercolumn with short wave solar radiation. The watercolumn subsequently stratifies and wind and convection induced mixing are insufficient to fully mix oxygen over the depth.

1. Introduction

During summer, stratified mid-latitude lakes often suffer from recurrent eutrophication and hypoxia, and there has been significant research into the causes and effects. Phytoplankton blooms (Twiss et al., 2012) and low oxygen (e.g., Mathias and Barica, 1980; Babin and Prepas, 1985) have also been observed to occur under winter ice; however, detailed studies coupling winter stratification to biogeochemistry are lacking, with most winter research focusing on fish adaptations to winter conditions.

Temperate lakes typically turnover twice a year (dimictic), once in spring and in fall, and the associated breakdown of stratification and enhanced vertical mixing re-oxygenates the bottom water during the turnover periods. Re-oxygenation occurs in both dimictic and monomictic lakes through the formation of convective currents (e.g., Fer et al., 2002), which may be inhibited when inter-annual variations in climate prevent turnover. For example, warm winter conditions have been shown to prevent turnover in monomictic Lake Biwa, leading to year-round hypoxia (Yoshimizu et al., 2010). This may be exacerbated, in monomictic lakes, by climate change-induced warming (Sahoo and Schladow, 2008); however, climate change effects over the next 100 years are not expected to be sufficient to prevent turnover of dimictic lakes (Bolkhari and Boegman 2012).

In the present study, we analyze four years of continuous temperature and oxygen observations from ice-covered Little Silver Lake (Ontario). The objectives are to characterize the evolution of stratification and hypoxia in the lake, as it responds to inter-annual climate variation, and investigate the vertical fluxes of buoyancy and oxygen during the fall and spring turnover events.

2. Methods

Little Silver Lake (Fig. 1) has a maximum depth of 12.2 m and a surface area of 0.86 km^2. The lake has a ~15 m deep north basin, which seasonally stratifies, and a ~6 m deep long and narrow south basin. The trophic status of Little Silver Lake remains difficult to define; the lake is eutrophic according to Secchi disk and chlorophyll observations and mesotrophic according to surface nutrient concentrations (RVCA, 2001). Bottom water nutrients are persistently and drastically above the Provincial Water Quality Objectives (e.g., total phosphorus is 15 times the objective), likely from sediment release during hypoxia, and pose a risk for triggering the observed eutrophication of surface waters and algae blooms. Developing an understanding of the role of stratification and watercolumn turnover on nutrient and oxygen cycling is of fundamental importance for lake management.

Field measurements were conducted from the RBR Freshwater Research Institute at Little Silver Lake. To measure the stratification and oxygen profiles in the lake, temperature (±0.002 °C) and oxygen (±2%) loggers (TDO-2050, RBR Ltd.) were moored at 1.5 m, 3.5 m and 6.5 m depths, at a 7.5 m deep site (Fig. 1), and sampled every 60 s from Nov. 14, 2007, through Jul. 21, 2011. Hourly averages are shown in the figures. Loggers were calibrated at RBR following standard procedures and the oxygen data was despiked using the phase-space method. The moored data were supplemented with casts from a watercolumn profiler (XRX-620, RBR Ltd.) equipped with depth (±0.05%), temperature (±0.002˚C), oxygen (±2%), turbidity (±2%), chlorophyll (±2%), conductivity (±3 μScm^{-1}), pH (±0.1) and PAR (±2%) sensors.

Daily average temperature data and Climate Normals were downloaded from Environment Canada (www.climate.weatheroffice.gc.ca) for Hartington (44° 25' 41.028" N; 76° 41' 25.086" W), which is 45 km south-west of Little Silver Lake, and meets WMO standards. These data are consistent with data from Drummond Centre, 30 km north-east of Little Silver Lake, showing that the off-site temperature data is characteristic to the region. Daily maximum wind gusts were downloaded for Ottawa International Airport (45° 19' 21" N, 75° 40' 9" W), located 86 km from Little Silver Lake.
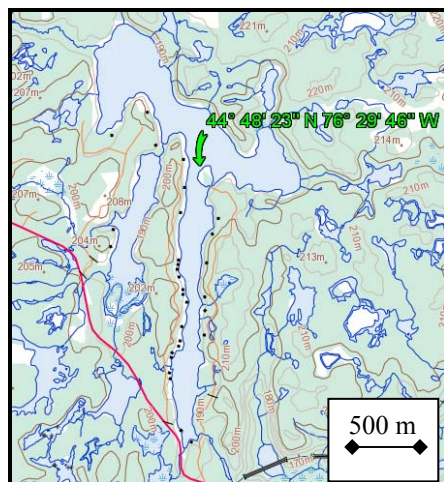

Figure 1. Maps of Little Silver Lake, Ontario (44° 48' 23.63" N, 76° 29' 46.58" W), showing location of mooring at 7 m deep field site. (http://atlas.nrcan.gc.ca).

3. Results

3.1 Temperature and Oxygen Profiles

The loggers were deployed during the fall turnover of 2007, when both temperature and oxygen concentrations were uniform with depth (Fig. 2). Fall turnover ended on Nov. 30, 2007, and the lake was ice-covered by Dec. 23, 2007 (Table 1). Characteristic 'reverse' winter stratification ensued, causing the bottom water to become hypoxic (<5 mgL^{-1}) by Dec. 18, 2007 (day 352, Figs. 2 and 3). The rapid spring turnover on April 19, 2008, was not sufficient to re-oxygenate the bottom water, causing hypoxic and anoxic (<1 mgL^{-1}) conditions to persist until Oct. 6 and Oct. 3, 2008, respectively. Interestingly, the onset of anoxia coincided with the rapid spring turnover, which only lasted 1 d. A metalimnetic oxygen maximum was observed near day 500 (Fig. 2) and is likely associated with photosynthesis (discussed below). Fall turnover from Oct. 5-Dec. 7, 2008, re-oxygenated the watercolumn. Ice cover was observed by Nov. 23, 2008, and winter stratification formed with hypoxia (Jan. 9-Apr. 5, 2009) and anoxia (Mar. 23-Apr. 3, 2009). Spring turnover during Mar. 26-Apr. 14, 2009, re-oxygenated the watercolumn until oxygen depletion occurred during summer stratification with hypoxia from Apr. 29-Sept. 28, 2009 (days 850-1002) and anoxia from Jun. 7-Sept. 26, 2009. Fall turnover was during Sep. 29-Dec. 9, 2009, with the lake freezing between Nov. 22 and Dec. 25. Winter hypoxia was delayed until Feb. 17, 2010, (day 1144) and again persisted through the spring turnover (Mar.17-25, 2010) and summer stratification until Sept. 28, 2010 (day 1367), with summer anoxia during May 13-Sep. 14, 2010. Fall turnover (Sep. 16-Dec. 4, 2010) mixed the watercolumn, followed by winter stratification and hypoxia over Feb. 13-Apr. 10, 2011 (days 1505-1561). Spring

turnover mixed the watercolumn from Apr. 6-23, 2011, and summer stratification began with hypoxia on 11 May and anoxia on Jun. 23. The observations are summarized in Tables 1 and 2.

Table 1. Characteristic observations from Little Silver Lake showing inter-annual variability in ice cover and turnover periods. Ice observations, based on irregular inspections, are approximate. Other data are from Fig. 2. N/A denotes data not available.

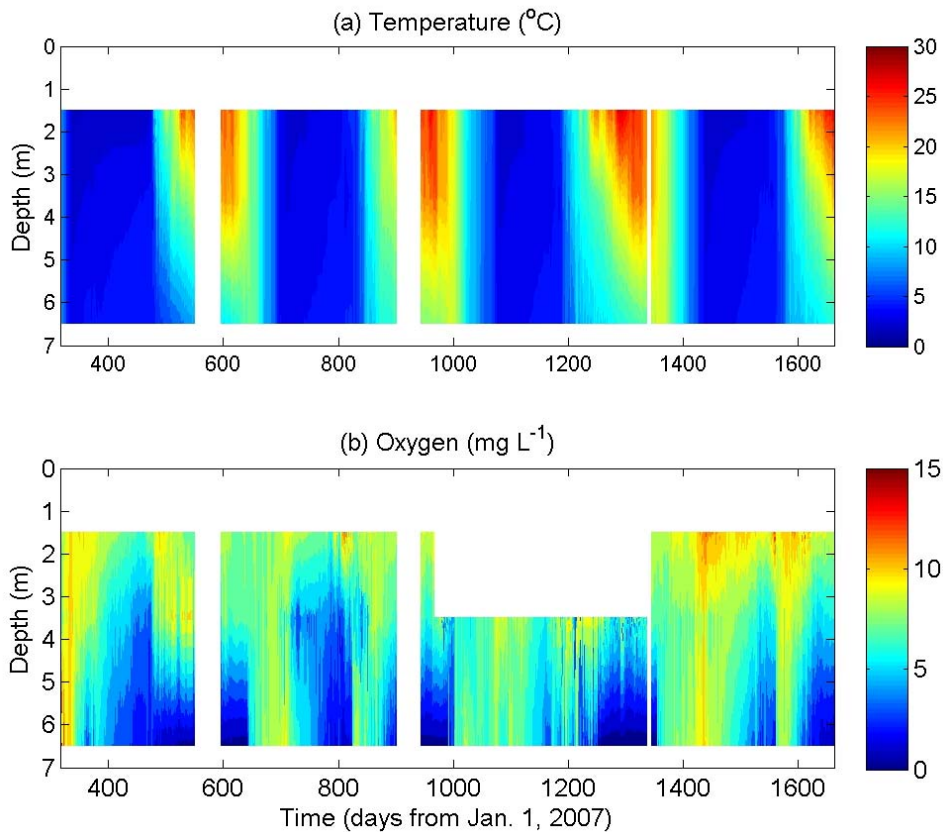|	2007	2008	2009	2010	2011
Ice off	Apr 6 (lake thawed)	Apr 13 (thawed at margins)	Apr 4 (most ice gone)	Apr 6 (ice melting)	N/A
Spring turnover	N/A	Apr 19 (1 d)	Mar 26-Apr 14 (19 d)	Mar 17-25 (8 d)	Apr. 6-23 (17 d)
Fall turnover	N/A -Nov 30	Oct 5-Dec. 7 (63 d)	Sep 29-Dec 9 (71 d)	Sep 16-Dec 4 (79 d)	N/A
Ice on	Dec 23 (lake frozen)	Nov 23 (ice on lake)	Nov 22-Dec 25 (freeze-up)	N/A	N/A

Figure 2. Depth vs. time contours of (a) temperature and (b) dissolved oxygen during 2007-11 from the mooring shown in Fig. 1. Data are contoured from loggers at 1.5, 3.5 and 6.5 m depths. Days 1-365, 366-731, 732-1096, 1097-1461 and 1462-1826 correspond to 2007, 2008, 2009, 2010 and 2011, respectively.

3.2 Coupling between Meteorology, Stratification, and Hypoxia

To better examine the coupling between stratification, hypoxia, and meteorology, we plot the temperature difference between water at 1.5 m and 6.5 m depths (Fig. 3a), the dissolved oxygen 0.5 m above the bottom (Fig. 3b) and the air and 1.5 m depth water temperatures.

Table 2. Characteristic observations from Little Silver Lake showing inter-annual variability in anoxia and hypoxia. Data are from Fig. 2. N/A denotes data not available.

Season	Hypoxia ($<$5 mgL^{-1})	Anoxia ($<$1 mgL^{-1})
Winter 2007-08	Dec. 18, 2007-Oct. 6, 2008 (293 d)	None
Summer 2008	See above	Apr. 19, 2008-Oct. 3, 2008 (167 d)
Winter 2008-09	Jan. 9, 2009-Apr. 5, 2009 (86 d)	Mar. 23, 2009-Apr. 3, 2009 (11 d)
Summer 2009	Apr. 29, 2009-Sep. 29, 2009 (152)	Jun. 7, 2009-Sep. 26, 2009 (111 d)
Winter 2009-10	Feb. 17, 2010-Sep. 28, 2010 (223 d)	None
Summer 2010	See above	May 13, 2010-Sep. 14, 2010 (124 d)
Winter 2010-11	Feb. 13, 2011-Apr. 10, 2011 (56 d)	None
Summer 2011	May 11, 2011-N/A	Jun. 23, 2011-N/A

The watercolumn shows a typical seasonal stratification cycle, with ~18 °C and ~2°C temperature differences between 1.5 m and 6.5 m during summer and winter, respectively. The corresponding near-bed oxygen data is not as regular. Characteristic summer and winter hypoxia are separated by well-mixed fall and spring turnovers, during winter 2008 though summer 2009 (days 650-1000) and winter 2010 through summer 2011 (days 1350-1700). However, long hypoxic (293 to 223 d, respectively) periods persist during the winter of 2007 through the summer of 2008 (days 850-1002) and the winter of 2009 through the summer of 2010 (days 1144-1367). These occur in warm years when the spring turnover is very short (1-8 d turnover, Table 1) and are associated with anomalously warm air temperatures and weak winds during spring (e.g., Fig. 3, 10-20 °C on days 473-483 and 1185-1195). The limited re-oxygenation during turnover results in long periods of summer anoxia (167 to 124 d), but the warm temperatures and likely limited winter ice cover prevent anoxia during the preceding winter. Comparison of annual monthly-average air temperatures to Climate Normals (Fig. 4) shows mean April air temperatures of 8.9 °C (2008) and 9.9 °C (2010) in the warm years, relative to the Normals of 6.2 °C (1961-1990) and 6.0 °C (1971-2000), to be sufficient to shorten spring turnover to $<$8 d (Table 1) and prevent full mixing of oxygen. This was not the case in the other years, when mean April temperatures were cooler at 7.2 °C (2009) and 6.3 °C (2011) and closer to the averages. In these years, spring turnover was $>$17 d (Table 1) and oxygen mixed throughout the watercolumn.

In years when the watercolumn fully re-oxygenates during fall and spring turnovers, winter and summer hypoxic periods are 56-86 d and 152 d, respectively, and anoxic periods are 0-11 d and 111 d, respectively; whereas in years when re-oxygenation only occurs during spring, hypoxia and anoxia persist for 223-293 d and 111-167 d, respectively. The overall length of hypoxic and anoxic periods in the warm and average spring years tends to balance (Table 2), the warm years having long summer oxygen depletion and oxic winters, whereas the normal years have shorter periods of depletion in both summer and winter. On average, hypoxia and anoxia persist for 251±37 d and 137±25 d (mean ± standard deviation), respectively, which is approximately 2/3 and 1/3 of the year. Hypoxia must, therefore, be considered as the characteristic state of the lake.

Detailed views of the temperature and oxygen profiles during the short and long spring turnover events (Fig. 5), show the long events to occur coincident with strong winds and low temperatures, whereas the short events are during calm winds and are during or immediately prior to warm air temperatures. Maximum daily wind gusts are roughly above and below 6 m s^{-1}

during the long and short spring turnovers, respectively, a value found to characterize when mean daily winds would mix a weakly stratified watercolumn (1-2 °C over 7 m) in western Lake Erie (Boegman et al., 2008a).
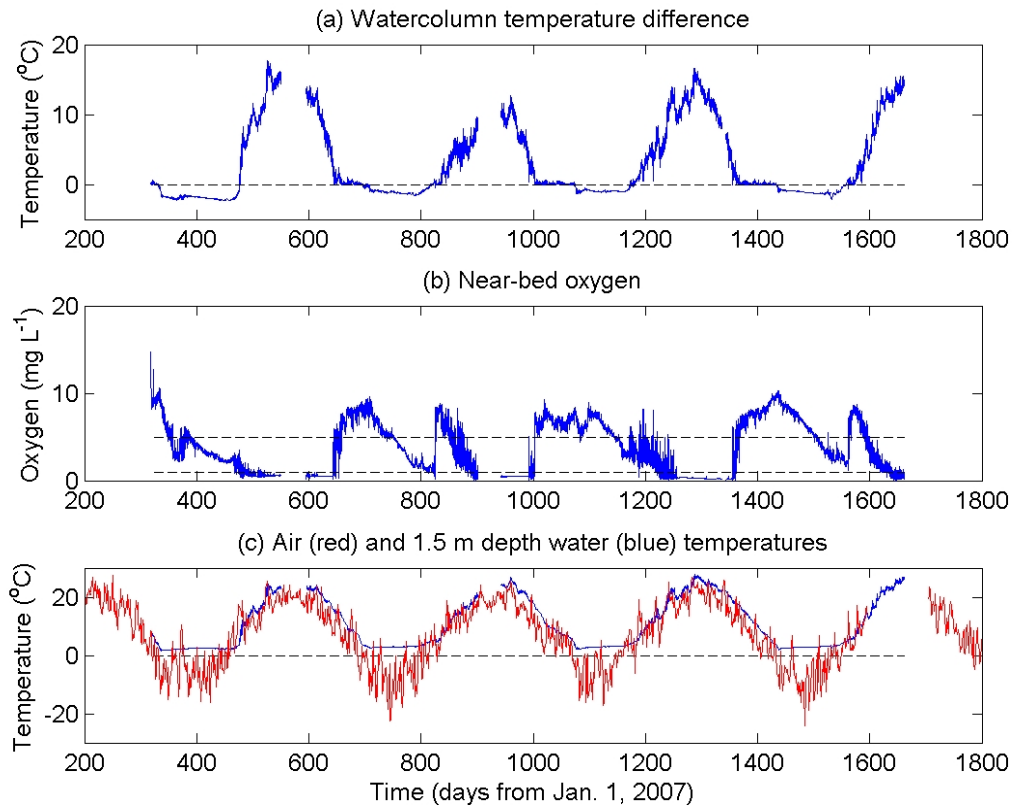

Figure 3. Timeseries of (a) temperature difference between 1.5 m and 6.5 m depths; (b) dissolved oxygen at 6.5 m depth and (c) air temperature and 1.5 m depth water temperature during 2007-11. All data are from the mooring shown in Fig. 1, except the air temperature data is from Hartington, Ontario (see Fig. 4). Days 1-365, 366-731, 732-1096, 1097-1461 and 1462-1826 correspond to 2007, 2008, 2009, 2010 and 2011, respectively.
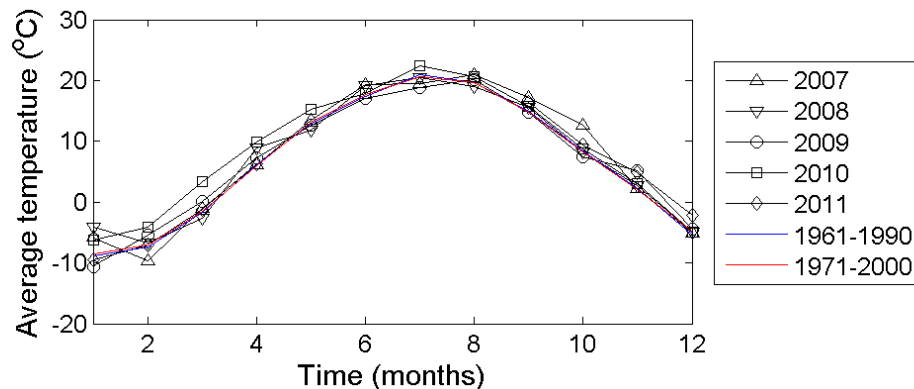

Figure 4. Comparison of annual monthly-average air temperature to Climate Normals at Hartington, ON (44°25'41.028" N; 76°41'25.086" W). Data from Environment Canada Station 6103367.
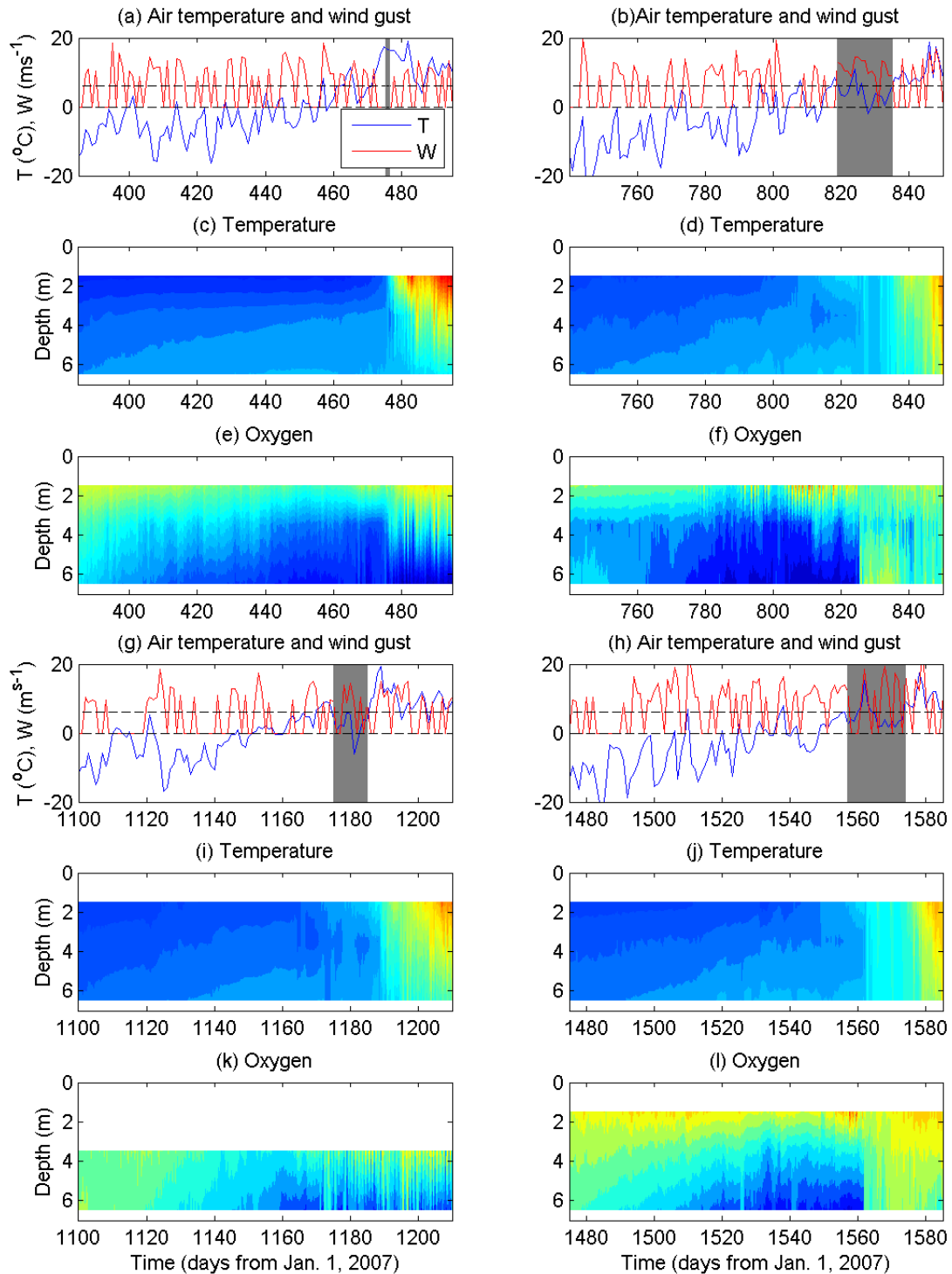
Figure 5. Detail showing short spring turnover events during 2008 (a), (c) and (e); and 2010 (b), (d) and (f); and longer turnover events in 2009 (g), (i) and (k); and 2011 (h), (j), (l). Wind speed (W) is the maximum daily gust observed at Ottawa International Airport and air temperature (T) is from Hartington. Gray shading denotes turnover period (Table 1). The oxygen colorbar is the same as in Fig. 2 and the temperature colorbar is half that in Fig. 2, ranging from 0 °C (blue) to 15 °C (red).

3.3 Watercolumn Biogeochemistry Profiles

The XRX-620 profiles show the variation of lake biogeochemistry throughout the year. During summer stratification (Fig. 6a), a thermocline is present at 6 m depth and the hypolimnion is hypoxic (~2 mgL^{-1}), with high turbidity, but low chlorophyll. High turbidity during hypoxia has also been observed in nearby Eagle Lake (unpublished), which is much deeper (max. depth = 31 m). PAR penetrates to a depth of 5 m and a chlorophyll maximum (~3.5 μgL^{-1}) occurs at the bottom of the photic zone. These observations are consistent with long term monitoring of the lake (1971-99) showing 4.4 m Secchi depths and 3.3 μgL^{-1} chlorophyll-a (RVCA, 2000). During winter ice-cover (Fig. 6b), the temperature follows the characteristic 'reverse' winter stratification profile, approaching zero at the surface and 4 °C near the bed. The slight increase in temperature at the sediment, from 4 to 4.5 °C, and elevated near bed salinity (in all 3 profiles) provide evidence of groundwater inflow, with dissolved oxygen approaching zero in the isolated brine layer. During fall turnover (Fig. 6c), all biogeochemical parameters are well mixed, with the exception of PAR, which penetrates to ~4 m, with reduced intensity relative to summer.
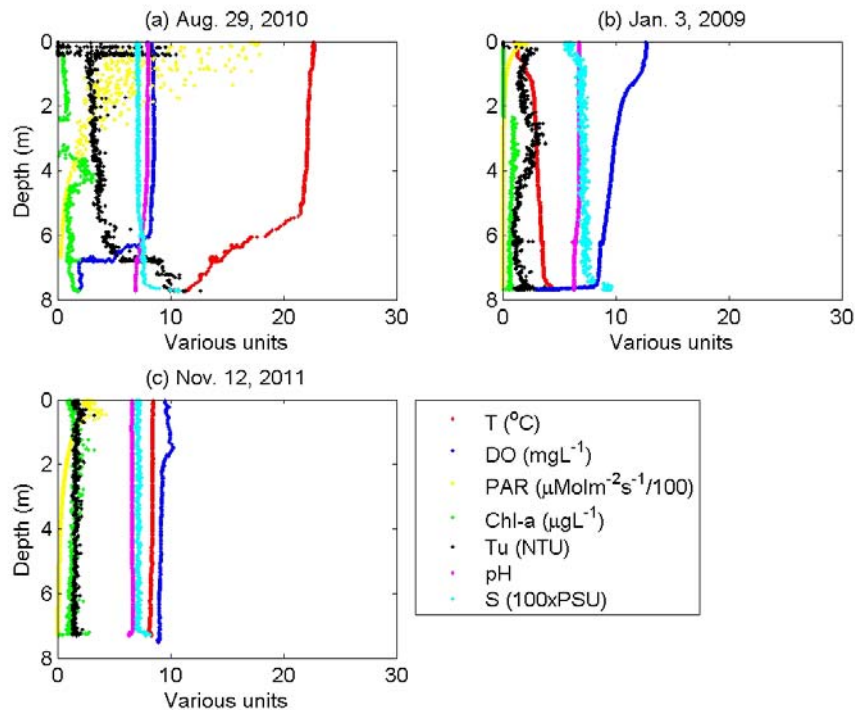

Figure 6. XRX-620 profiles during (a) summer stratification, (b) winter ice-cover, and (c) fall turnover. Profiles show temperature (T), dissolved oxygen (DO), photosynthetically active radiation (PAR), chlorophyll-a (Chl-a), turbidity (Tu), pH and salinity (S).

4. Discussion

We have established that long (> ~2 week) spring turnover events are sufficient to fully mix heat and oxygen and throughout a 7 m watercolumn, and that short (< ~1 week) turnover events will result in uniform temperature, but not oxygen profiles. Similar observations have been made in the Dorset Lake region (Molot et al., 1992).

During fall, the stratification is much stronger than spring (~15 °C vs. ~3 °C, Fig. 3a) and the required buoyancy flux to mix the water column is delivered over a longer timescale (Farmer

1975; Imberger 1985; Boegman 2009). This causes extended vertical flux through the watercolumn and the opportunity for wind-induced mixing, during neutrally stratified periods, leading to significant vertical transport of heat and oxygen.

During spring, we first investigate if the differential mixing of heat and oxygen may be related to differences in the associated source and sink terms for the heat and oxygen budgets; as it is typically assumed that in turbulent flows, scalars with different molecular diffusivities (e.g., heat and oxygen) will mix at the same rate according to the turbulent diffusivity (i.e., Reynolds analogy, see Bouffard and Boegman 2012). For example, Boegman et al. (2008a) found that heat and algae would readily mix through a 7 m watercolumn in western Lake Erie, in response to storm events, but benthic grazing by zebra mussels rapidly depleted the near-bed algae concentrations, forming a concentration boundary layer and dissimilar vertical profiles of heat and algae, immediately following the mixing events. There is potential for the sediment oxygen demand to have the same effect. During rapid spring turnover, the limited oxygen that reaches the bed may be readily consumed by the sediment oxygen demand (SOD). During the spring turnovers of 2008 and 2010, the near-bed oxygen concentration, $C \approx 5$ gm^{-3} (Fig. 3 near days 475 and 1200), with a hypolimnion thickness $H \approx 2$ m (Fig. 2) and a typical SOD ≈ 0.5 gm^{-2}d^{-1} (e.g., Boegman et al., 2008b). The oxygen will be consumed in CH/SOD = 20 days, which is significantly greater than the observations (Figs. 1 and 5), and so this hypothesis is not supported by simple calculations. There is no evidence of resuspension of sediments or algae (Fig. 6c) during convective turnover (e.g., Kelley, 1997), which may increase sediment surface area and/or enhance respiration/photosynthesis and so these biogeochemical processes are likely not relevant at this time. Near-bed heat sources, such as groundwater inflows (see T and S in Fig. 6b) and sediment heating from solar radiation (see PAR in Fig. 6) are also negligible during turnover. Photosynthesis (and associated oxygen production) sharply decreases with depth, following the PAR profile (Fig. 6), and so and respiration below the photic zone may augment SOD and consume vertically transported oxygen (Carrick 2004); we have no data to test this. However, unpublished oxygen isotope measurements, from the Experimental Lakes Area, confirm incomplete mixing of near-surface and near-bottom watercolumn oxygen during analagous short spring turnovers (J. Venkiteswaran, U. Waterloo, pers. comm.).

If not mixing through turbulence, the uniform temperature profiles may be explained to result from solar heating. The theoretical clear-sky heat flux from shortwave solar radiation on Apr. 1 penetrates through the entire watercolumn according to the Beer-Lambert Law (Fig. 7c), with an extinction coefficient of 1.7/(Secchi depth), and is in agreement with PAR observations (Fig. 6). The heat imparted, $dT=I(z)/(4181.3$ J(Kg°C)$^{-1}$) by shortwave radiation, $I(z)$ Wkg^{-1} (Fig. 7c), is sufficient to turnover the watercolumn in 1 d, without mixing, and begin spring stratification (Fig. 7d). If coupled with warm and calm weather conditions (Fig. 5), spring turnover may be accomplished without transporting oxygen toward the bed. The heat flux driving convection is much less than the shortwave flux. For an air-to-water temperature difference of 15 °C and mean daily wind speeds of 0, 3 ms^{-1} (average annual speed at nearby Eagle Lake) and 6 ms^{-1} (wind speed required to mix a weakly stratified 7 m watercolumn in Lake Erie; Boegman et al., 2008a) the sensible heat fluxes, due to conduction, are 0, 70 and 140 W m^{-2}, respectively (Fig. 7c).

Molot et al. (1992) investigated 33 Canadian Shield lakes and found the extent to which spring re-oxygenation occurred during turnover to be a function of lake surface area and fetch, as

opposed to lake depth relative to photic depth (Fig. 7c); suggesting that wind mixing plays an important role. For small and large oligotrophic lakes, respectively, spring mixing was poor when the maximum fetch was ≤0.6 km or ≤0.9 km, complete when ≥1.3 km or ≥1.4 km and otherwise partial (Fig. 7a). The Molot et al. (1992) data does not show similar correlations between the degree of spring turnover and the ratio of lake depth to the photic depth (Fig. 7b). These results suggest the following model for spring turnover in shallow lakes. Solar heating of the watercolumn can cause turnover of the temperature profile without mixing the water column in <1d. When coupled with calm conditions and warm air temperatures, spring stratification will ensue and near bed water will remain hypoxic from winter through summer. However, typical temperatures and strong wind events, which are more pronounced in lakes with long fetches and large surface areas, will cause the weakly stratified watercolumn to physically mix and turnover the oxygen profile.
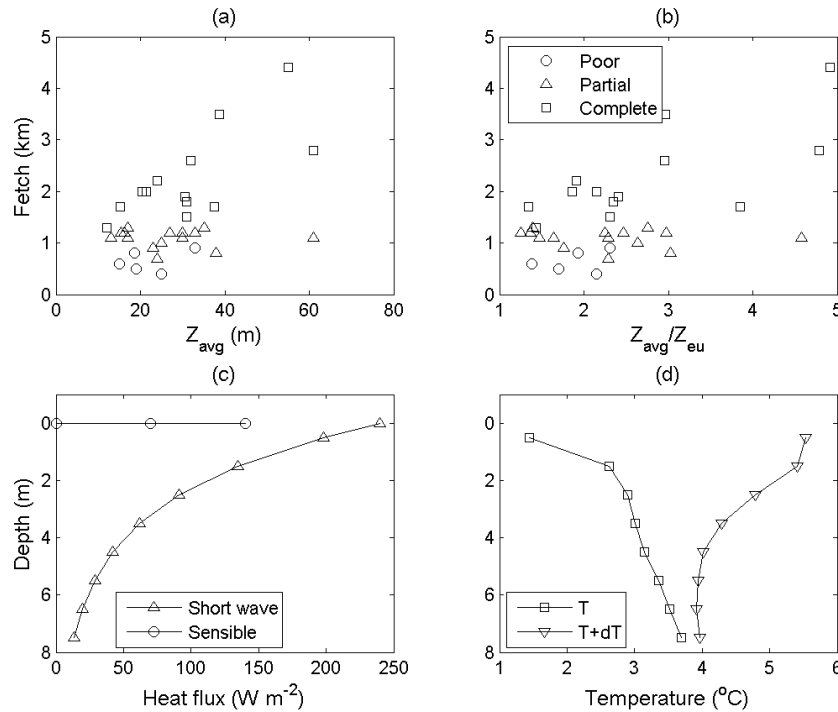

Figure 7. Fetch vs. (a) average depth, Z_{avg}, and (b) Z_{avg} over euphotic depth, Z_{eu} = 5(Secchi depth)$^{0.5}$ from Molot et al., (1992) for lakes with poor, partial and complete spring oxygen turnover. (c) Clear-sky shortwave radiation (Apr. 1) and sensible heat flux (winds of 0, 3 and 6 ms^{-1} and 15 °C temperature difference) and (d) observed temperature (*T*) profile (from Fig. 6b) and temperature profile increase (*T+dT*) from shortwave radiation applied over 1 d. Little Silver Lake has a fetch of ~1 km and has partial mixing. Secchi depth = 4.4 m (RVCA, 2000).

Penetrative convection will be relatively negligible in small shallow lakes where horizontal gradients are likely not significant. Turbulent mixing is suppressed under ice cover (Oveisy et al., 2012), but significant horizontal transport is generated by convection and seiches (Colman and Armstrong, 1983; Stefanovic and Stefan, 2002; Forrest et al., 2008). However, in deeper lakes, horizontal gradients resulting from differetial heating/cooling will be significant. The heat storage capacity of the deeper watercolumn will prevent rapid turnover and subsequent stratification, and full mixing of both oxygen and heat profiles is expected during the longer turnover events. Gravity currents will form in the shallow littoral zones, which cool/heat faster

than offshore, and cascade toward the benthos, carrying oxygen (Fer et al., 2002; Yoshimizu et al., 2010; Wells and Sherman, 2001).

5. Conclusions

The lake exhibits near-bed hypoxia and anoxia 2/3 and 1/3 of the time, respectively, with the watercolumn resetting to atmospheric oxygen levels only during fall and long spring turnover events. Short spring turnovers, which occur during anomalously warm and calm weather conditions, result in a uniform temperature profile, by directly heating the entire watercolumn with shortwave radiation. The watercolumn subsequently stratifies and wind/convection induced mixing is insufficient to cause turnover, which would mix oxygen throughout the watercolumn. Our chlorophyll observations suggest that the lake is mesotrophic, and the high near-bed concentration of phosphorus will remain sequestered during the majority of the year, except at turnover. The nutrient pulse during turnover events may trigger bloom activity but this has not been observed.

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