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Long-term changes in hypolimnetic dissolved oxygen in a large lake: Effects of invasive mussels, eutrophication and climate change on Lake Simcoe, 1980–2012

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ABSTRACT

Lake Simcoe has been influenced by multiple environmental drivers over the past decades, especially by reductions in phosphorus (P) loading, climate change, and invasive species such as dreissenid mussels (DM) which became firmly established in 1996. We examined the cumulative impact of these drivers on the volume-weighted hypolimnetic dissolved oxygen concentration (VWHDO) below 18 m at station K42 in Kempenfelt Bay during ice-free seasons from 1980 to 2012. Hypolimnetic DO depletion began in early spring when thermal stratification was observable but weak and continued throughout the ice-free season until cooling sufficiently lowered water column stability. In comparison to the pre-DM invasion period (1980–1995), mean annual $\mathrm{VWHDO_{init}}$ was 2.4 mg L^{-1} higher in the post-DM period (1996–2012), $\mathrm{VWHDO_{min}}$ was 1.54 mg L^{-1} higher and the mean duration of the depletion period (L) was 16 days longer. Mean DO depletion rate (DR) and temperature adjusted DO depletion rate ($\mathrm{DR_{adj}}$) were slightly lower (7% and 5%, respectively) after 1996. P controls and DM had a positive effect on VWHDO, presumably by lowering productivity and diverting organic matter away from the hypolimnon. However, longer L apparently offset improvements in $\mathrm{VWHDO_{min}}$. If lengthening of L associated with regional warming continues, then additional efforts to reduce P loads will be necessary to achieve the goal of maintaining $\mathrm{VWHDO_{min}}$ above the target of 7 mg O_2 L^{-1} throughout the summer and fall.

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Introduction

Lake Simcoe, the largest inland lake in southern Ontario outside the Great Lakes, is an invaluable natural, social, and economic resource. Lake Simcoe has six drinking water treatment plants (WTPs) that provide drinking water to several communities in the watershed. It also assimilates wastewater from 14 municipal water pollution control plants (WPCPs) and one commercial treatment plant. Expenditures associated with recreational fishing on the lake were estimated at $33.7 million (Ontario Ministry of Natural Resources and Forestry, 2013). However, Lake Simcoe and its watershed have experienced multiple pressures from increasing human activities over the past ~200 years, including logging, damming, canal construction, agriculture, urban development, species invasion and recently climate change (Hawryshyn et al., 2012).

Coldwater fish require cold temperatures and high dissolved oxygen (DO) concentrations to survive (Gibson and Fry, 1954; Rudstam and Magnuson, 1985), and consequently are sensitive to anthropogenic stresses that raise water temperatures or lower DO concentrations, for example, climate change (Sharma et al., 2011) and eutrophication (Welch et al., 2011). Elevated inputs of nutrients (e.g. phosphorus (P) and nitrogen (N), essential elements that support and maintain aquatic life) to the lake result in excess growth of phytoplankton, which settle and decompose consuming DO by respiration. Elevated microbial respiration rates are especially problematic in the bottom layer of thermally stratified lakes because inputs of new DO after stratification are typically very low until the lake mixes in the fall. Under climate change as air temperatures are expected to increase, surface water (epilimnion) temperatures are expected to increase accordingly (Sharma et al., 2015) as is the duration of the lake thermal stratification period (Stainsby et al., 2011), thereby isolating the deep waters from top well oxygenated water for a longer period. With both stresses in mind, Ficke et al. (2007) proposed a "temperature oxygen squeeze" scenario for coldwater fish habitat.

Coldwater fish have a suitable temperature niche between 5 and 15 °C (most commonly below 8 °C; Plumb and Blanchfield, 2009) and a dissolved oxygen threshold of 6–7 mg L^{-1} below which maximum bioenergetic power output is reduced (Evans et al., 1996; Evans, 2007), and a DO concentration below 3 mg L^{-1} is considered lethal to many coldwater fish species (Evans et al., 1996). After ice-out, coldwater fish such as lake trout inhabit surface water for feeding (Martin, 1970) and as the epilimnetic water temperature warms, they retreat to deeper water (Fry and Kennedy, 1937; Fry, 1939) which marks the cessation of surface feeding until fall overturn (Martin, 1970). Previous research

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suggests that earlier stratification forces earlier migration of all ages of lake trout to deeper, colder waters, curtailing intense spring feeding and consequently reducing growth (King et al., 1999). DO continuously decreases after spring overturn in deeper waters even before development of a thermocline although strong mixing events can introduce DO downward. Keeping in mind that low oxygen levels will harm the coldwater fishery, an end-of-summer minimum volume-weighted hypolimnetic dissolved oxygen (MVWHDO) target of 7 mg L^{-1} by September 15 was set by the Lake Simcoe Protection Plan (LSPP) as the optimal target to restore a self-sustaining coldwater fish community (LSPP, 2009). Although, in theory, longer stratification periods due to climate change (Stainsby et al., 2011) could lead to lower hypolimnetic oxygen in late summer months no empirical analysis has been done until this study to evaluate to what extent the hypolimnetic DO has changed due to long term trends in climate change and other factors in Lake Simcoe.

In this paper, our overall goal was to examine long-term patterns of volume-weighted hypolimnetic dissolved oxygen (VWHDO) dynamics, an important indicator of coldwater fish habitat, in relation to major environmental changes in the past three decades. These changes include eutrophication followed by P reduction beginning in the late1980s (Young and Jarjanazi, 2015), introduction of invasive dreissenid mussels, which had become well established by 1996 (Evans et al., 2011), and climate change post 1980. Specific objectives were three-fold: first, to examine annual thermal structure patterns and their long-term trends; second, to examine trends in VWHDO dynamics including spring VWHDO, VWHDO depletion rate, the length of the VWHDO depletion period and minimum ice-free VWHDO; and third, to determine the relative influences of major environmental stresses on VWHDO dynamics.

Methods

Study site

Lake Simcoe, located in southern Ontario between Georgian Bay of Lake Huron to the northwest and Lake Ontario to the southeast (Fig. 1), is a large, relatively shallow lake (area $A = 722\ km^2$, mean depth $\bar{z} = 14$ m, maximum depth $z_{max} = 42$ m, shoreline perimeter = 303 km, volume $= 11 \times 10^9\ m^3$, residence time = 11 years) with a watershed area of 2899 km^2 and 35 tributaries (Evans et al., 2011; North et al., 2013; Winter et al., 2007). Kempenfelt Bay ($A = 35.74\ km^2$, $\bar{z} = 26$ m, $z_{max} = 42$ m) contains the deepest part of the lake and exhibits thermal stratification.

Lake Simcoe is shallow relative to its surface area, which is evident from a low morphometric ratio (Osgood Index$= \frac{\bar{Z}}{\sqrt{A_0}}$, Osgood, 1988) of 0.52. The morphometric ratio for Kempenfelt Bay alone is much larger at 4.35.

Data acquisition, and field and laboratory methods

Temperature profiles, DO profiles, water chemistry, and morphometric data for Lake Simcoe were provided by the Ontario Ministry of the Environment and Climate Change (MOECC). The MOECC monitored water quality in Lake Simcoe at station K42 in Kempenfelt Bay (Fig. 1) from 1980 to 2012. The station was sampled every two weeks through ice-free period (typically, May to November). Integrated water samples were obtained through the euphotic zone (defined as 2.5 times the Secchi disk depth to a maximum depth of 15 m) using a polyvinyl chloride (PVC) hose for chemical analysis (total P (TP), total Kjeldahl N (TKN), total nitrate ($NO_2 + NO_3$), ammonia (NH_4), alkalinity, chlorophyll *a*, sulfate (SO_4), calcium and silica). Temperature and dissolved oxygen profiles were measured at K42 using a YSI probe at 1-meter intervals to the bottom and Secchi disk depth was defined as the water depth in meters at which a black and white Secchi disk was no longer visible to an observer at the surface (Winter et al., 2011). VWHT is the mean summer (July–September) volume-weighted hypolimnetic water temperature (calculated as below for VWHDO).

Daily air temperature data were obtained from Environment Canada's weather station (http://climate.weather.gc.ca/) at Shanty Bay, which is 10 km northeast of the city of Barrie and close to station K42 in Kempenfelt Bay.

Estimates of annual TP loading were available for years 1990–2011. Methods for estimating TP loads have changed over the years but are based on the best available data at the time. Methods are described in Scott et al. (2001, 2006), O'Connor et al. (2012, 2013, 2017) and Winter et al. (2002, 2007).

Ice phenology (on and off dates) has been observed by volunteers since 1853 in Lake Simcoe. Data are available from the NatureWatch national volunteer monitoring program until 1995; observations continued to be submitted to the MOECC after 1995 by a private citizen who participated in the NatureWatch program.

Data analysis

Timing of thermal stratification onset and termination were calculated from Schmidt's stability index, *S* (Hutchinson, 1957; Idso, 1973; Schmidt, 1928), as follows:

$$S = A_0^{-1} \sum_{Z_0}^{Z_m} \left(z - z_{\bar{\rho}}\right)(\rho_z - \bar{\rho}) A_z \Delta z$$

where *S* is the Schmidt's stability index (g cm cm^{-2}), A_0 is the surface area of the lake, $z_{\bar{\rho}}$ is the depth at which the mean density is found, ρ_z is the density of the water at depth z, $\bar{\rho}$ is the mean density of the water column, and A_z is the stratum area at depth z. The summation is taken over all depths (z) at intervals (Δz) of 1 m from the surface (z_0) to the maximum depth (z_m). Water density was calculated based on Millero and Poisson (1981) and Martin and McCutcheon (1999). This index is a measurement of water column stability and indicates the amount of mechanical work required to mix the lake to an isothermal condition (the temperature of water at mean density). A high value of *S* indicates strong stratification requiring more energy to mix; a low value of *S* indicates near isothermal condition requiring low energy to mix. A subjective threshold of 800 g cm cm^{-2} was considered to be the stability at which onset of stratification occurred in spring at station K42 (Stainsby et al., 2011). This threshold approximately reflects the establishment of a thermocline (defined by a temperature difference > 1 °C within a 1 m interval) in the water column. *S* was calculated using the "schmidt.stability" function in "rLakeAnalyzer" package (Winslow et al., 2014; Read et al., 2011).

To determine the beginning and end of the defined thermal stratification period, *S* curves were divided into ascending and descending limbs and linear and polynomial regressions were fitted to each limb. The best fit was selected using ANOVA and used to estimate the days on which $S = 800$ occurred in the spring and fall. Instantaneous rates of increase and decrease of *S* in spring and fall, respectively, were determined by the selected regression model. Average *S* during stratification was calculated as the sum of *S* for each day during the stratification period divided by the length of the period in days.

VWHDO is generally defined as the DO below the upper limit of the hypolimnion following Quinlan et al. (2005). In Lake Simcoe, to ensure that calculated hypolimnetic DO did not include oxygenated water mixed from above (and obfuscate estimation of depletion rates from heterotrophic respiration and nitrification), an upper ceiling for the tropholytic zone was set at 18 m for DO modeling (Nicholls, 1997). Therefore, VWHDO was calculated for each sample date using the following formula:

$$VWHDO = \frac{\sum_{42}^{18} bathV_i \times DO_i}{V_{hypo}}$$

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