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Wash-zone dynamics of the thermocline in Lake Simcoe, Ontario

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ABSTRACT

Lake Simcoe exhibits substantial thermal variations during the stratified period and rapid temperature changes along the zone where the thermocline intersects with the lake bed. The observed wind-driven thermocline movements are analyzed and discussed based on high-frequency measurements made in August and September 2011 and from a 30-year record of bi-weekly temperature profiles. Winds with speeds exceeding 5 m s^{-1} drive large-amplitude internal seiches on an approximately weekly timescale. The projected wash-zone associated with these thermocline motions stretches over a quarter of the total surface area where rapid changes in the benthic temperature of as much as 5 °C/h occur. A major new finding of this work is that the mean depth of the thermocline scales favorably with the depth at which surface waves tend to redistribute only finer sediment and the associated substrate changes above and below this boundary. In lakes where this scaling applies, we hypothesize that wash-zones can be associated with dynamic habitat bounds (ecotones) due to thermal variability and a substrate type transition from muds to sand. Thus, thermocline movements in stratified, similar-sized lakes and the links to physio-biological processes should be further scrutinized, in particular with ongoing climate change and fast warming water bodies.

Introduction

Upwelling of cold hypolimnetic waters and downwelling of warm epilimnetic waters occur in all lakes due to internal waves and seiches triggered by strong wind events (Hawley and Muzzi, 2003; Hlevca et al., 2015; Troy et al., 2012; Wells and Parker, 2010). The motion of these water masses by internal seiches results in important temperature variability around the mean depth of the thermocline and can also induce intensive benthic boundary mixing (Chowdhury et al., 2016). In turn, these processes have a major control on physiological processes and the ecology of the water body (Cyr, 2012, 2016; Evans et al., 2008; Finlay et al., 2001; Magnuson et al., 1979; Spigarelli et al., 1982). The physical significance of temperature fluctuations prevalent in temperate lakes has previously been acknowledged, but few studies have linked observations of thermal variability to biological processes (Ludsin et al., 2014; Coulter et al., 2015a, 2015b). As water temperature is a key ecological determinant for ectothermic organisms, we will document how large the spatial extent of these persistent and important temperature changes at the lake bed can be, which has been overlooked in past studies of fish habitat usage.

The magnitude of internal seiche motions and associated temperature variability in stratified lakes depends on wind speed, wind duration, fetch length and strength of thermal stratification (Shintani et al., 2010). During increased surface wind stress, the thermocline is depressed at the downwind end of the lake, while upwelling occurs at the upwind end (see Fig. 1; Fischer et al., 1979, and references therein). When wind stress decreases, the position of the thermocline starts to oscillate about its mean depth driving thermal variation and benthic currents at the lake bed. The vertical scale of thermocline excursions can be many meters in lakes, in particular when coupled with a gently sloping lake bed (Hawley and Muzzi, 2003; Cossu and Wells, 2013). The excursions can result in an extensive area where the thermocline washes back and forth along the lake bed (hereinafter the 'wash-zone').

In addition, with sufficient fetch, surface waves run ashore at the downwind end of a lake (Fig. 1a). The wave base indicates the depth at which wave-induced dynamics vanish so that erosion and sediment transport is less prevalent beyond the wave base. This process is known as "sediment focusing" and leads to accumulation of finer sediments in deeper parts of lakes while coarse particles predominantly remain in shallow areas (Blais and Kalff, 1995). It follows that the type of

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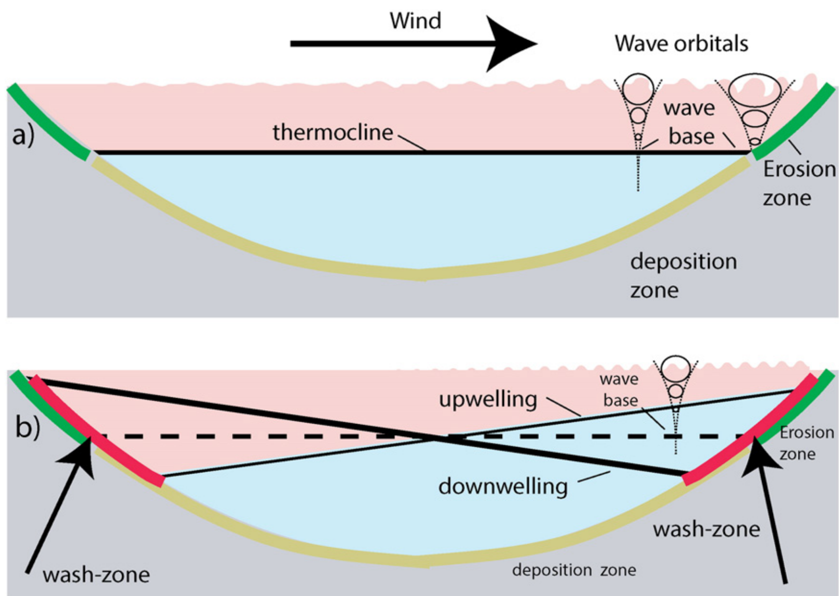

Fig. 1. a) Due to wind forcing, surface waves build at the downwind end of the lake. The orbital velocity is a function of wave height, and decreases with depth. The maximum depth at which erosion occurs is known as the wave base. Thus, the wave base separates areas of erosion (green) and deposition (light-brown) as only finer sediments can be transported to the deeper parts of the lake. b) The thermocline oscillates in the depth range between $z_{thm} \pm \Delta z_{th}$, which is defined as the wash-zone (red). z_{thm} is the average depth of the thermocline and Δz_{th} the excursions above and below this average depth. The range of the wash-zone indicates that temperature variability in a stratified system can occur in both the erosion and deposition zones (i.e., between hard and soft substrates.

substrate depends on the location relative to the wave base and the prevailing sediment transport regime.

We will show mathematically that the depth range of the thermocline has an empirical scaling (Gorham and Boyce, 1989), which scales similarly to the depth of wave bases in large lakes. This phenomenon implies that these two important depth scales could overlap in many lakes in the Great Lakes region (see next section), which is a novel and general result not previously reported. This overlap underlines the significance of the location of the thermocline as an ecotone as upper and lower thermal boundaries, as well as substrate changes, lie within its physical location (Cadenasso et al., 2003; Strayer et al., 2003). Thus, the position of the wash-zone could be important, in particular with respect to ongoing climate change and its impact on thermal regimes in temperate lakes (Ficke et al., 2007). Furthermore, the position of the wash-zone may have strong implications for an ecosystem such as for benthic secondary production and even to some extent to fish occupancy (Szekeres et al., 2016). The variability and extension of the wash-zone could also play a role for fish occupancy during near-bottom hypoxia (Arend et al., 2011; Vanderploeg et al., 2009).

In this study, we focus predominantly on thermocline movements observed in Lake Simcoe, Ontario, which is known for its dynamic thermocline (Baird and Associates, 2006; Bouffard and Boegman, 2011; Chowdhury et al., 2015) and large temperature variability in the wash-zone (Cossu and Wells, 2013). We quantified the temperature variability using both high-frequency data collected during a strongly stratified period in summer 2011 and long-term records (1980–2011) of the thermal structure. Anoxia can often develop beneath strong thermoclines in many lakes, so temperature variability in a wash-zone also implies dissolved oxygen variability. We discuss our findings with respect to the importance of linking physical and biological variables to improve and advance future monitoring programmes in the Great Lakes region.

Methods

Field site

Our field study was conducted in Lake Simcoe (44°25′ N, 79°30′ W), a large dimictic lake located in Ontario, Canada (Fig. 2). It is the largest inland lake of southern Ontario with a total surface area of 722 km^2, a total volume of 11.6 km^3, and an elevation of 219 m above sea level. The lake has one main basin with two side arms, Kempenfelt Bay in the west and Cook's Bay in the southwest. The main basin is roughly circular with a gentle sloping shallow eastern half, and steep slopes on the western side. Our field site was located on the southeastern shore of the main basin where there is a gentle slope of 1.5 m/km. The lake has a maximum depth of 41 m, with a mean depth of 20 m and a maximum effective fetch of 30 km. It is oligotrophic with a mean thermocline depth of 10 m, where typical summertime surface temperatures reach 20–22 °C in the epilimnion and 8–10 °C in the hypolimnion (Stainsby et al., 2011). Stratification is strongest during hot summer months (July to early September), which determined the period and duration of our observations.

Lake Simcoe has suffered from water quality problems since the 1970s and has experienced severe environmental changes (North et al., 2013), including problems with low hypolimnetic oxygen in deeper regions favoured by the coldwater fish community. The Draft Lake Simcoe Protection Act (2009) targets an ecologically sustainable state, which is based on a self-sustaining coldwater fish community and a deep-water dissolved oxygen target concentration of 7 mg L^{-1}. An important change in Lake Simcoe has been observed since zebra and quagga mussels (*Dreissena polymorpha* and *D. bugensis*) started to colonize the lake since 1995 and 2004, respectively, which has caused dramatic changes to water clarity, benthic biomass, and food-web structure (Evans et al., 2011). These mussels are most abundant on harder substrate in depths between 5 and 15 m (Technical Progress Series in Lake Monitoring: Report No. 2, 2014), and so they live near the mean depth of the thermocline.

Instrumentation

Prevailing winds usually blow from the west and northwest during late summer in Lake Simcoe. Wind speed and direction were measured from the hourly records of the Environmental Canada meteorological station located at the western shore of Lake Simcoe near Barrie airport (44°29′ N 79°33′ W, Fig. 1).