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Parameterization of bottom mixed layer and logarithmic layer heights in central Lake Erie

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ABSTRACT

The bottom boundary layer in lakes lies directly above the sediments and influences both hydrodynamic processes and biogeochemical fluxes. Several parameter-based models have been developed to predict the boundary layer characteristics, but the relative accuracy and applicability of these models remains under investigated, particularly for the Great Lakes. Here, high-resolution velocity and temperature data were analyzed to characterize temporal variations in the thicknesses of bottom mixed layer and logarithmic layer in central Lake Erie. We considered both weakly and strongly stratified periods, when these layers were primarily forced by surface seiches and near-inertial waves, respectively. Existing equations to predict the height of the bottom mixed layer (h_{mix}) were calibrated and evaluated using the observed h_{mix}, the bed-shear velocity, and the local Brunt–Väisälä frequency at the top of h_{mix}. We found that $h_{mix} = 1.8u_*/f\left(1+N_o^2/f^2\right)^{1/4}$, where u_* is the shear velocity and f and N_o are the inertial and the local Brunt–Väisälä frequencies, respectively. The logarithmic layer height was also delineated using fit results from classical and modified law-of-the-wall equations. The fitting results were validated by comparison of the shear velocities to independent results from the structure function method. Stratification was shown to have negligible effect on the shear stresses within the log layer; however, the stratification term was required, at times, to describe the observed velocity profile for heights >1.5 m above the bed. Overall, our results show the thickness of logarithmic layer is a poor predictor for h_{mix} in Lake Erie.

Introduction

In lakes and coastal waters, turbulence in the bottom boundary layer regulates the flux of biogeochemical parameters between the water column and the sediments by reducing near-bed scalar gradients (e.g., temperature and nutrients) and leads to the formation of a bottom mixed layer, in which the water density is almost constant (Spigel and Imberger, 1980; Lueck and Lu, 1997). Through this region, there is an increase in the mean horizontal velocity away from the no-slip condition at the bed, which often follows the well-known logarithmic law-of-the-wall profile (Wüest and Lorke, 2003; Scalo et al., 2013). A knowledge of the bottom mixed layer height is important for closing energy budgets in lakes (Wüest, 2000; Bouffard et al., 2012), and for calculating nutrient and oxygen fluxes between the sediments and the overlying water column (Fischer et al., 1979; Lorke and MacIntyre, 2009).

Measurements to compute the bottom mixed layer height are not always available, resulting in a need to develop parameterizations from other flow variables. However, parametric models have not been developed and tested for the Great Lakes. These models typically depend on two key parameters, the vertical profile of the mean horizontal velocity (or the shear velocity), and the inertial frequency (Kundu, 1976; Perlin et al., 2007). The relative accuracy and applicability of the various models remains under investigated. For density-stratified systems, space–time variability in the bottom mixed layer height is influenced by basin-scale internal waves (Marti and Imberger, 2006). With stratification, the Brunt–Väisälä frequency profile becomes another contributing variable (Weatherly and Martin, 1978; Lorke and MacIntyre, 2009). Accordingly, the bottom mixed layer height has been defined as the layer above the bed where temperature or density changes are small (e.g., ≤2×10^{-2} °C, Johnson et al., 1994; ≤10^{-2} kg m^{-3}, MacKinnon and Gregg, 2005; ≤6×10^{-4} kg m^{-3}, Perlin et al., 2007). However, small density gradients do have the ability to damp vertical mixing (e.g., Boegman et al., 2008; Pernica et al., 2014).

There has been considerable research on the vertical extent of the logarithmic law-of-the-wall velocity layer near the bed (Grant and Madsen, 1986; Cheng et al., 1999); compared to limited research on the bottom mixed layer. Previous studies show law-of-the-wall fit results (i.e., shear velocity and bottom roughness) depend strongly on the distance above the bed and depth range selected for the fit. The

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thickness of the logarithmic layer is also different from the thickness of the bottom mixed layer (Johnson et al., 1994; Taylor and Sarkar, 2008).

In this study, we focus on the central basin of Lake Erie, where near-bed turbulence regulates the height of the bottom mixed layer and controls the flux of oxygen between sediments and the overlying hypoxic hypolimnetic water (Rao et al., 2008; Bouffard et al., 2013). In the offshore regions of central Lake Erie, the surface winds energize basin-scale barotropic (surface) seiches and near-inertial baroclinic (internal) Poincaré waves with periods of ~14 h and ~17 h, respectively. The surface seiches and Poincaré waves, respectively, induce oscillatory and steady anticyclonic bottom boundary layer flows, which energize near-bed turbulence and mixing. These motions are the predominant basin-scale forcing processes in central Lake Erie (Rao et al., 2008; Valipour et al., 2015) that regulate the bottom mixed layer height. The central basin hypolimnion is relatively thin (<10 m), and so the Coriolis force, which acts on the baroclinic motions (Valipour et al., 2015), only forms an Ekman boundary layer in the deeper (~65 m) eastern basin (Bedford and Abdelrhman, 1987). We are unaware of published observations of the bottom mixed layer height from Lake Erie although limited observations exist of the logarithmic layer height (Bedford and Abdelrhman, 1987; Ackerman et al., 2001).

The objective of the present study is to analyze high-resolution near-bed velocity and temperature data to better parameterize the temporal changes in the bottom mixed layer heights in Lake Erie. Results from existing parameterizations were calibrated and evaluated against observations of bottom mixed layer height and also compared to the vertical extent of the logarithmic law-of-the-wall velocity layer.

Measurements and methods

Study area

Lake Erie (Fig. 1a; 388 km long and 92 km wide) is the shallowest of the Laurentian Great Lakes and consists of distinct western, central, and eastern basins, which have maximum depths of 11 m, 25 m, and 64 m, respectively. The lake has an inertial period of 18 h (or inertial frequency $f \sim 0.97 \times 10^{-4}\ \mathrm{s}^{-1}$).

Field measurements

In the summer of 2009, high-resolution temperature and velocity measurements (Fig. 1 and Table 1) were carried out in central Lake Erie at station (Sta.) 341. Water temperatures were recorded at 0.1 Hz using temperature loggers (TR-1060, RBR Ltd. accuracy $\pm 2 \times 10^{-3}$ °C). A 1.8-m tripod was also deployed on the bottom at a depth of 17.5 m (Fig. 1b). The tripod was equipped with upward and downward-looking acoustic Doppler current profilers (ADCPs; Nortek with accuracy of ±1% of measured values; Fig. 1b and Table 1). The upward-looking 600-kHz ADCP burst recorded velocity every 15 min at 1 Hz over 180 s in 1 m bins to the surface (Figs. 2b,d,g,i). The downward-looking 2-MHz pulse coherent HR-ADCP burst recorded velocity every 15 min at 1 Hz over 256 s in 3 cm bins to the bed (Figs. 2c,e,h,j). Meteorological data were obtained from an Environment Canada meteorological buoy at Sta. 341, that recorded standard meteorological variables, including 10 min average wind speed and direction (Figs. 2a,f).

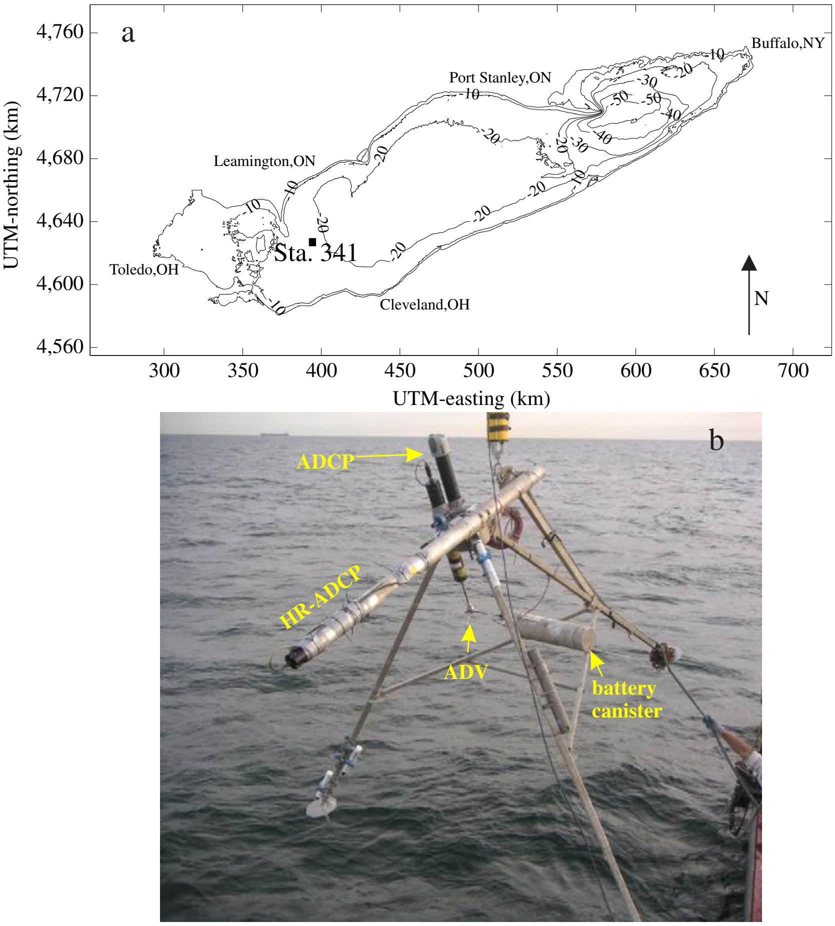

Fig. 1. (a) Map of Lake Erie with bathymetric contours (in meters), the black rectangle shows the location of Sta.341, and the axis is based on Universal Transverse Mercator coordinate system (UTM) in zone 17-North. (b) The 1.8-m tripod equipped with upward-looking ADCP and downward-looking HR-ADCP before deployment at Sta.341.