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Investigating the effect of the Coriolis force on internal wave dynamics and flushing of a coastal embayment

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Abstract

Lake Simcoe is a large (SA = 722 km2), mid-latitude (44° N lat.) lake in Canada that suffers from high nutrient loading and eutrophication. The 42 m deep Kempenfelt Bay on the western side of the lake contains the majority of the cold-water fish habitat and is also prone to end-of-summer hypolimnetic hypoxic conditions. A better understanding of the exchange dynamics of Kempenfelt Bay is essential for enacting long-term water quality improvements. Using high resolution temperature and current velocity field data from 2015, we show that large-amplitude internal waves have a significant impact on the current velocity structure of Kempenfelt Bay. The internal waves act as bellows, pumping water into and out of the embayment. Moreover, the Coriolis force causes the currents to be deflected to the right, resulting in an asymmetrical flow structure with predominantly westerly flows on the north side, and easterly on the south side of the bay. The asymmetry sets up a residual counter clockwise flow in Kempenfelt Bay that could further impact flushing.

1 Introduction

Internal wave dynamics in large, mid-latitude lakes are controlled by a complex interplay of Coriolis, geostrophic and buoyancy forces which contribute to the development of complicated physical processes in a lake's embayments. Exchange between an embayment and the main basin of a lake is often constrained, leading to the development of unique water characteristics within the embayment that are strongly influenced, both spatially and temporally, by its flushing dynamics.

Many of the physical processes governing the flushing dynamics of embayments have been previously investigated, such as tidal currents (Kuo and Neilson, 1988; Sanford et al., 1992; Hartnett et al., 2003) and differential heating/cooling (Burling et al., 1999; Wells and Sherman, 2001; Wells and Sealock, 2009). Spatial thermal variations due to upwelling events (baroclinic forcing) have been shown to be the dominant exchange mechanism in bays (Rueda and Cowen, 2005) and harbours (Hamblin and He, 2003; Lawrence et al., 2004) that are connected to the main basin by a narrow channel. In contrast Trebitz et al. (2002) and Hlevca et al. (2015) found that surface seiches (barotropic forcing) can have a significant impact on the flushing and exchange rates of wetlands and shallow natural embayments, particularly when shallower than the thermocline. The influence of baroclinic forcing in the form of internal waves in deep embayments has not received significant attention. This paper aims to address this knowledge gap by investigating the influence of large-amplitude internal waves on the thermal and current velocity profile of a Coriolis-influenced, mid-latitude embayment.

Kempenfelt Bay is a 15 km long, narrow embayment (2 km wide) located on the west side of Lake Simcoe, Canada (see Figure 1). The lake suffers from eutrophication and chronic end-of-summer hypolimnetic hypoxic conditions. Bouffard and Boegman (2011) have demonstrated, using both field and numerical simulation data, the presence of basin-scale internal waves in Lake Simcoe, and Cossu and Wells (2013) have investigated the influence of these waves on turbulence at the benthic boundary layer during upwelling and downwelling events. It has been shown by Chowdhury et al. (2015) that mixing between the surface and bottom layers in Lake Simcoe is infrequent and episodic, with very low vertical mixing rates across the metalimnion ($K_z \sim 10^{-6}\ m^2s^{-1}$). Studies modeling the bay's water quality rely on estimates for flushing rates (Gudimov et al., 2012) which can lead to large uncertainties in their results. Using field data collected in 2015, our talk will contribute to a fuller understanding of the physical processes in Kempenfelt Bay and other comparable systems such as the Petit Lac of Lake Geneva and the Überlingen arm of Lake Constance.

2 Methods

From August 6th to September 20th, 2015, detailed measurements of Kempenfelt Bay's thermal and current structure were taken in an effort to characterize the dominant physical processes taking place in the bay. The results of this measurement campaign and an analysis of their flow characteristics will be undertaken in the Results and Analysis section.

Six thermistor strings were deployed in Kempenfelt Bay, three on the north side and three on the south spaced approximated 5 km apart, as show in Figure 1. Each string consists of 16 temperature loggers spaced at 1 m intervals (top 3 are 2 m apart) sampling every 5 minutes. Two ADCP were also placed on the north and south sides of Kempenfelt Bay (Figure 1), measuring the water current velocity in 1 m bins with sampling periods of 5 (north) and 10 (south) minutes (mean of 300 readings per sampling period taken at 1 Hz). Instruments were placed in approximately 25 m water depth.

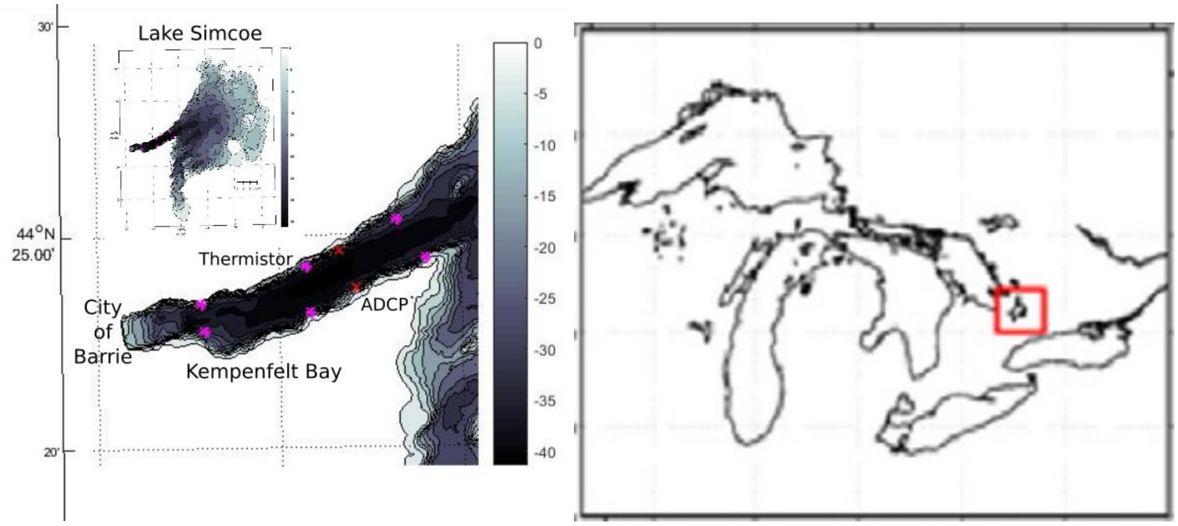

Figure 1: Lake Simcoe bathymetry and instrument deployment locations, 2015. Topographical lines at 4 m spacing. Magenta asterisks' represent thermistor strings (Numbered from west to east: north side; 1, 3, 5 and south side; 2, 4, 6), and red Xs ADCPs. On the right hand side is Lake Simcoe's location with respect to the Laurentian Great Lakes. Image courtesy of Chowdhury et al. (2015): doi:10.1016/j.jglr.2015.07.008.

3 Results and Analysis

Lake Simcoe was strongly stratified throughout the whole observation period, with the stratification starting to weaken in the last few days (DOY 260 onwards in Figure 2). The 12°C isotherm, an important criteria delineating cold-water fish habitat, is used as a proxy for the thermocline. It was determined via linear interpolation between thermistors and has been plotted as a solid black line.

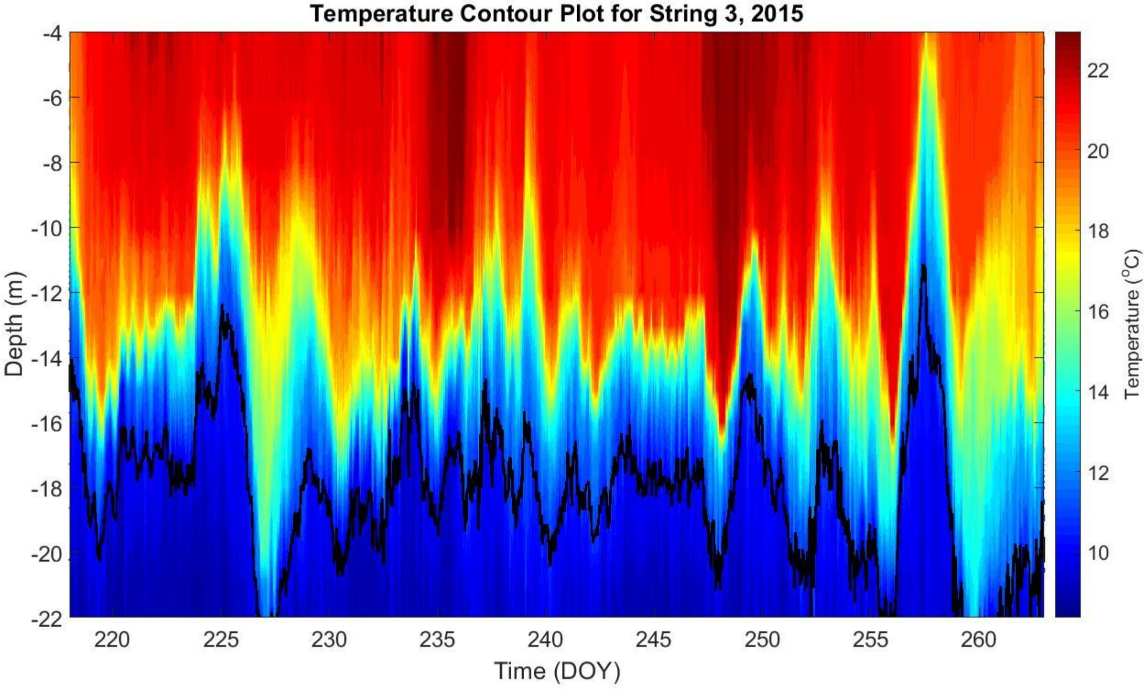

Figure 2: Temperature contour plot for Kempenfelt Bay (String 3). Black line is 12C isotherm.

Wind forcing on the lake's surface results in the development of internal waves that propagate along the metalimnion, clearly shown in Figure 2, with observed amplitudes in excess of 12 m and associated periods (determined by spectral analysis) of approximately 3 days. Bouffard and Boegman (2011) have shown that basin-scale internal waves, or internal seiches, in the main basin of Lake Simcoe develop into coastally constrained internal Kelvin waves due to the Coriolis force, with a period of approximately 3.5 days, which is consistent with the 2015 field observations. As the internal Kelvin wave enters the narrow bay, its structure is modified due to the constraining influence of the adjacent shoreline. Specifically the embayment width of 2 km is similar but smaller than the internal Rossby radius of deformation of 3.7 km.

The constant rising and falling of the thermocline plays a significant role in the flushing dynamics, acting as a bellow, continually pumping water into and out of the bay due to the limited exchange across the metalimnion (Chowdhury et al., 2015). As water flows into and out of Kempenfelt Bay, it is acted upon by the Coriolis force resulting in an asymmetrical velocity structure.

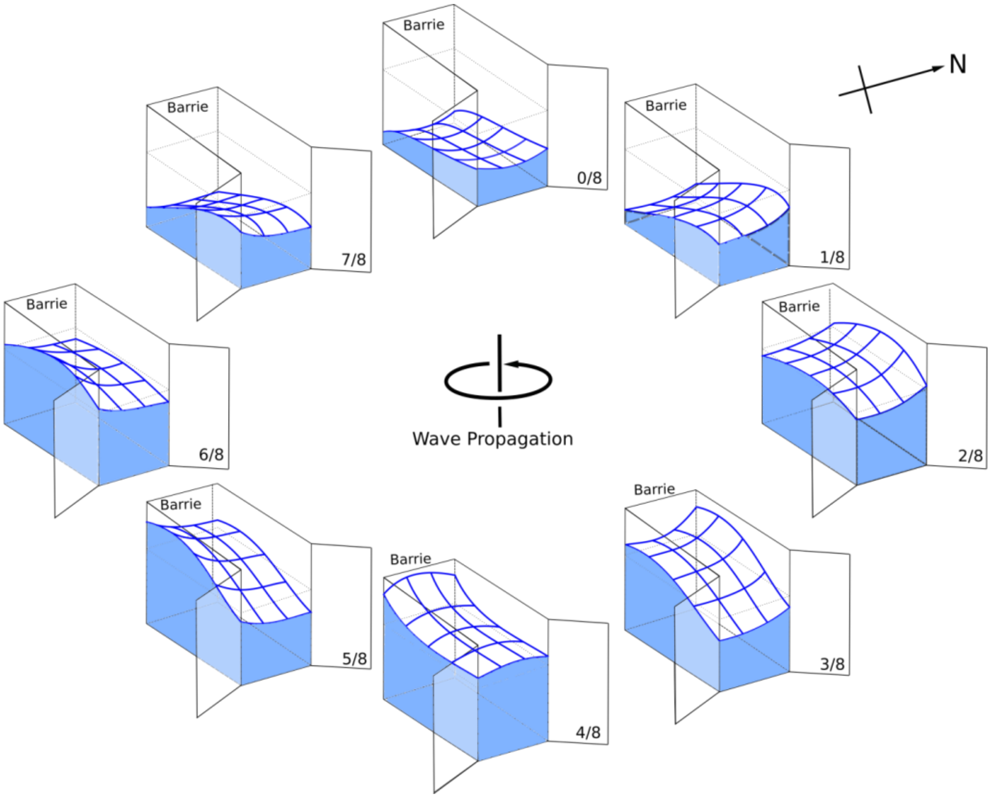

Figure 3: Successive phases (1/8 cycle) of internal Kelvin wave in a coastal embayment

This asymmetry, which can be clearly seen in the ADCP velocity data (Figure 4), has been idealized in the Figure 3 schematic. In order to maintain a constant surface water level, as the thermocline rises from trough to crest (phase 0 to phase 4 in Figure 3), hypolimnetic water is drawn into the bay, and epilimnetic water is forced out, in an easterly direction. The Coriolis force deflects the epilimnetic waters to the right with respect to the direction of propagation, resulting in a depression of the thermocline on the south side of the bay (and a corresponding thermocline tilt from north to south – positive values of dh/dy (magenta line) in Figure 4) and generally faster easterly along-shore currents along the south shore, as evidenced in the ADCP data in Figure 4. The opposite can be observed in the second half of the wave period; as the thermocline drops from crest to trough (phase 4 to 7 in Figure 4), epilimnetic water is drawn into Kempenfelt Bay from the main basin, and forced out below the thermocline in the hypolimnion. As the epilimnetic waters flow westward into Kempenfelt Bay, the Coriolis force deflects them to the right, resulting in faster velocities, and a depressed thermocline on the north shore, relative to the south (negative values of dh/dy). This is also supported by the ADCP current velocity data shown in Figure 4, where a dropping thermocline corresponds to predominantly westerly flows (negative/blue), with greater magnitudes on the north side.

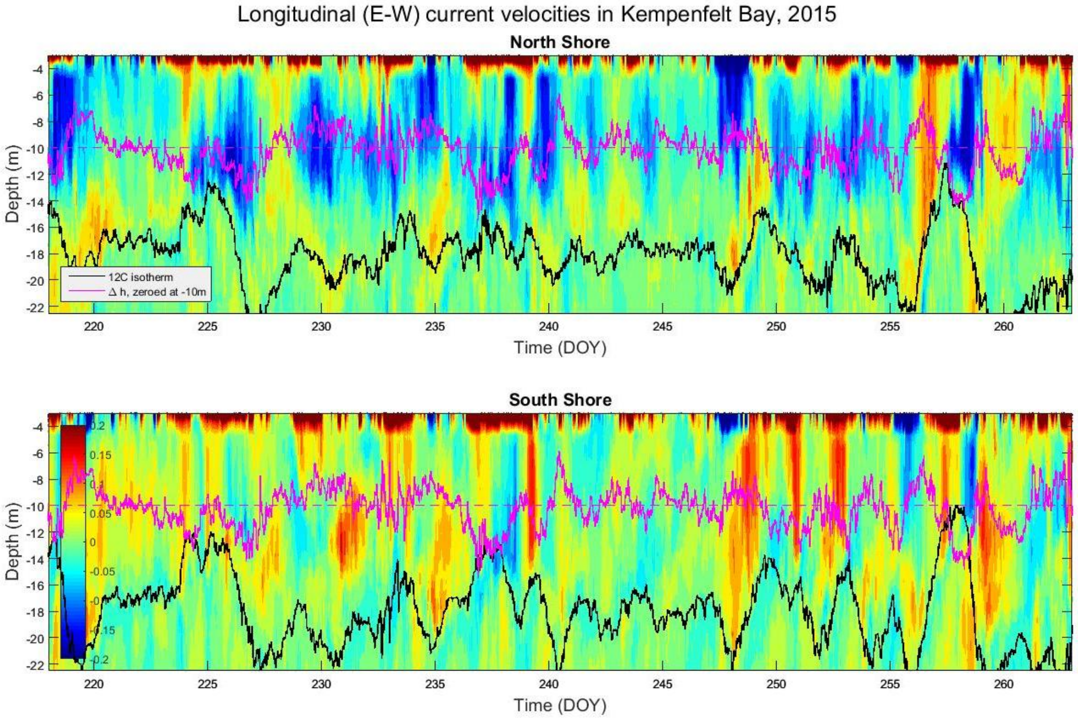

Figure 4: Current velocity profile in Kempenfelt Bay. Positive (red) is easterly; negative (blue) is westerly. 12°C isotherm is superimposed in black. Magenta line is the tilt of the thermocline (dh/dy) across Kempenfelt Bay, zeroed at -10 m. Positive values (> -10 m) indicate a tilt from north to south.

Residual flows as shown in Figure 5, interpreted here as mean along shore current velocities, reinforce the asymmetric flow structure within Kempenfelt Bay seen in the velocity data. Below the wind influenced surface waters, a mean westerly (negative) current on the north side of the bay and a mean easterly (positive) current on the south side predominates. Mean thermocline depth during the observation period was 18.3 m below the surface (averaged across the bay at thermistor strings 3 and 4). The residual flow structure rotating counter-clockwise around the bay suggests another mechanism for a continuous exchange of waters between the embayment and the main basin.

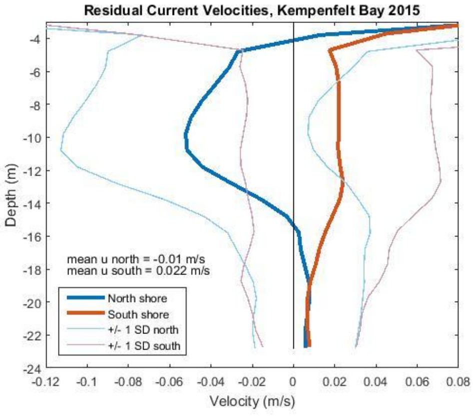

Figure 5: Residual flow in Kempenfelt Bay. Mean thermocline depth is -18.3 m.

The mean counter clockwise rotation of the flow in Kempenfelt Bay, inferred from the ADCP velocity contour plot (Figure 4) and residual flows (Figure 5), corresponds to a counter clockwise propagating wave front (depicted schematically in

Figure **3**) as evidenced by the propagation of the rising/sinking thermocline show in Figure 6.

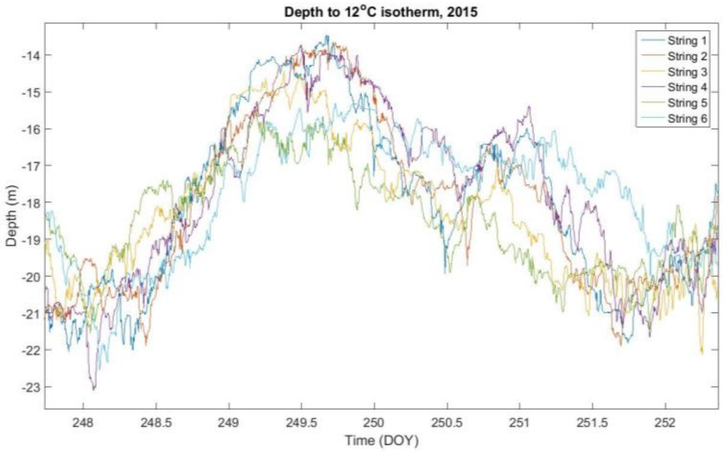

Figure 6: Depth to 12°C isotherm for all 6 strings (Strings, from west to east, are numbered: North: 1, 3, 5 and South: 2, 4, 6) for a select period during the 2015 observation campaign. Note how depth fluctuations are led by String 5, followed by 3, 1, 2, 4 and 6, indicating a counter clockwise rotation of the wave front.

4 Conclusions

High resolution temperature and current velocity data obtained during the stratified summer and fall period of 2015 suggest that thermocline movements in Kempenfelt Bay play a significant role in governing the exchange processes between the bay and the main basin. Moreover, these field data sets clearly indicate the influence of the Coriolis force on thermocline structure; both in its tilt across the bay, and in its counter-clockwise propagation around Kempenfelt Bay. The Coriolis force also has a significant influence on the water current structure within Kempenfelt Bay. Thermocline dynamics pump water into and out of the embayment, resulting in a predominantly counter-clockwise flow structure as seen in the asymmetries in the ADCP velocity profiles and the residual currents. A similar flow structure could be anticipated in the hypolimnion, offset by a half period from that of the epilimnion. Kempenfelt Bay has comparable dimensions to many mid-latitude coastal embayments in the Great Lakes and fjords in British Columbia and Scandinavia. As such, the processes discussed in this paper are likely to be found in other, comparable systems allowing the results to be widely applicable.

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