Internal waves pump waters in and out of a deep coastal embayment of a large lake

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Abstract

Large internal waves are a ubiquitous feature of many thermally stratified lakes, and result in oscillating baroclinic flows that pump water into and out of deep coastal embayments. In the long, narrow, and deep Kempenfelt Bay of Lake Simcoe, we show that stratification and circulation were coupled, so that movements of the thermocline can effectively flush the embayment much faster than hydraulic residence time from river input alone. Internal currents were driven by long-period internal waves and resulted in large horizontal excursion lengths of several kilometers, which could drive exchange of embayment waters with the main basin. If the embayments are long, wide, and deep, Coriolis forces also deflect the internal wave to follow the coastline on the right-hand side in the direction of travel as a Kelvin-type wave, resulting in a net cyclonic circulation in the embayment. This residual counterclockwise flow further facilitated flushing of Kempenfelt Bay. For the summer of 2015, we estimate that forced and free internal wave dynamics alone resulted in a seasonally averaged flushing timescale as short as 17 ± 6 d for the surface mixed layer, and of 13.5 ± 5 d for the hypolimnetic waters of Kempenfelt Bay. Kempenfelt Bay is representative of many long, deep, and narrow embayments found in the Laurentian Great Lakes and arctic fjords. The exchange processes investigated here are relevant for determining the dynamics of water quality parameters used as indicators to evaluate lake health and fish habitat.

Wind-induced large amplitude internal waves are a ubiquitous feature of large thermally stratified lakes, and the resulting oscillating baroclinic flows have the potential to pump waters in and out of coastal embayments that have depths greater than the thermocline. For example, typical internal wave amplitudes are of order 10 m with periods of 1–2 d in most of the Great Lakes (Rao and Murthy 2001; Bouffard et al. 2012; Austin 2013; Chowdhury et al. 2016) and amplitudes of 5–10 m are observed in Lake Simcoe (Chowdhury et al. 2015; Cossu et al. 2017). In particular, a number of studies in long, deep, stratified lakes have discussed the importance of internal seiche pumping in the lateral transport of dissolved oxygen (DO) and suspended sediments (Lawrence et al. 1997; Laval et al. 2008; Valipour et al. 2018). Thus, internal seiches can act as an important but under-recognized mechanism for exchange between the shallow littoral regions or embayments of lakes, and deeper offshore pelagic waters.

If the embayments are themselves wide and long enough, the form of the internal wave may be modified by the Earth’s rotation so that it is deflected to follow the coastline on the right-hand side as a Kelvin wave (Wüest and Lorke 2003). Kelvin waves are coastally trapped waves that decay exponentially offshore and form as the pressure balances the Coriolis force (Wüest and Lorke 2003). The wave has highest amplitudes of both velocity and thermocline displacement at the lateral boundary and then decreases with a decay scale equal to the Rossby radius, \( \rho_0 = c_i f \), where \( c_i \) is the internal phase speed and \( f \) is the Coriolis parameter (Antenucci et al. 2000). Such Kelvin waves would result in a net counterclockwise circulation pattern in long, narrow, and deep coastal embayments that would contribute to flushing (Inall et al. 2015). For instance, Umlauf and Lemmin (2005) observed significant exchange flows between the Petit Lac and Grand Lac of Lake Geneva that were due to internal Kelvin waves. This may be an important mechanism to flush many of the large coastal embayments of the Great Lakes.

The flushing time of a body of water is a crucial parameter controlling the structure of aquatic ecosystems, by means of
regulating water quality parameters such as road salts (Wells and Sealock 2009) or nutrients (Rueda and Cowen 2005b), which can drive lake eutrophication (Vollenweider 1976) and the occurrence of harmful algal blooms (Bricelj and Lonsdale 1997). In a steady state, well-mixed system, the concentration of a substance is related to the loading rate into the system multiplied by the flushing time divided by the volume. A number of mechanisms have been proposed to be important for the flushing of different-sized coastal embayments, including surface level fluctuations (Trebitz et al. 2002; Hlevca et al. 2015), wind-driven currents (Razmi et al. 2014), differential heating (Wells and Sherman 2001; Wells and Sealock 2009), and baroclinic exchange due to lateral temperature gradients (Lawrence et al. 2004; Rueda and Cowen 2005a). While these studies have focused on relevant processes for relatively small embayments, larger and deeper systems, especially those where internal waves are present, are likely to be controlled by internal wave pumping processes, which may be modified by Coriolis forces.

Due to the relatively small vertical density differences when stratified, the internal wave field in a large lake can respond strongly to rotational effects (Cushman-Roisin 1994). This influence is quantified by the internal Burger number $S_i$, a dimensionless ratio of advective to rotational forces:

$$S_i = \frac{c_i}{fL}$$

where $c_i$ is the nonrotating internal phase speed, $L$ is the length scale, and $f$ is the Coriolis parameter ($1.018 \times 10^{-4}$ s$^{-1}$ at 44.5°N). The Burger number is the ratio of the Rossby length-scale (over which the Kelvin wave decays from the coast) to the relevant length-scale of the system (the width of the basin). Rotational effects become important when $S_i$ is less than or of order 1, i.e., the system has a width greater than the length-scale of a Kelvin wave. While Coriolis effects for large lake systems are usually described in the context of small Burger numbers (Bouffard et al. 2012), systems that have $S_i$ of order 1 will still show some influence of Coriolis in that there will be lateral tilting of the longitudinal internal seiche, and the associated velocity will decay with distance from shore. For instance, even in a relatively small 3 km long lake, where Burger numbers ranged temporally with stratification from 0.83 to 1.71, Bernhard (2013) determined that the dominant seiche period was controlled by Coriolis effects. Similarly, Hamblin and Carmack (1978) observed the Earth’s rotation modified long-period internal waves in the 29 km long and ≈ 2 km wide Kamloops Lake in British Columbia where $S_i \approx 0$ (1). In addition to the lake systems described above, large embayments, with respect to the Rossby radius, can also be influenced by rotational effects. For example, in the Petit Lac of Lake Geneva (2.4–3.5 km wide and 18 km long), Bouffard and Lemmin (2013) observed significant lateral tilts of the thermocline across the bay associated with the propagation of internal Kelvin waves from the Grand Lac of Lake Geneva that also resulted in along-shore velocity decaying exponentially offshore. While these studies establish the influence of rotation on the internal-wave field of moderately sized systems, the observation campaigns were typically unable to observe details of how the Coriolis force modified the internal waves due to limitations in the experimental setup.

Residual circulation and net flushing in long and deep embayments can be controlled by baroclinic processes when the thermocline and hypolimnion are permanently coupled with the main basin. Long and deep embayments are dynamically similar to ice-free coastal fjords, which usually are strongly stratified with a freshwater layer above seawater. The stratified layer responds to tides from the stratified ocean, in an analogous manner to how an embayment might respond to internal seiches in a lake. Fjords occur at high latitudes, and hence the Coriolis force is large and Rossby radius is small. The important result relevant for lakes is that fjords have been shown to have tidally forced internal wave fields strongly modified by rotational effects (Inall and Gillibrand 2010). Indeed, Støylen and Weber (2010) concluded that tidally generated internal Kelvin waves produce a counterclockwise (Northern hemisphere) circulation and net transport of water and water quality constituents (e.g., salt). This is further supported by findings of greater sediment deposition and meltwater accumulation on the right-hand-side, looking down-fjord, for two narrow Greenland fjords by Gilbert et al. (1998). Due to similarities in the stratification, geometry, and forcing, large, thermally stratified embayments in temperate lakes are expected to exhibit analogous responses to salt-stratified fjords, and hence may also have a counterclockwise residual circulation. Umlauf and Lemmin (2005) investigated how episodic internal Kelvin-type waves drive exchange processes between the main basin of Lake Geneva and its western arm, the Petit Lac. They found that large-amplitude internal Kelvin waves were able to irreversibly exchange up to 40% of the hypolimnetic water in the Petit Lac over the course of a few wave cycles. However, their analysis focused on processes derived from a single wind event utilizing data from one current profile and four temperature profile locations positioned throughout the whole lake, making it difficult to determine realistic, long-term exchange dynamics. While many studies have identified the ubiquitous nature of internal waves in the Great Lakes, we are not aware of other high spatial and temporal resolution studies that have addressed their role in driving residual current, transport, and exchange in long, narrow, and stratified embayments.

Due to its simple channel-like geometry, Kempenfelt Bay in Lake Simcoe (Fig. 1) provides a natural laboratory to study how internal waves drive residual circulation and exchange between long, deep embayments, and the main basin of a lake. Bouffard and Boegman (2011, 2012) observed and modeled an internal Kelvin wave in the Kempenfelt Bay and Lake Simcoe system with a period of $\approx 90$ h, providing a mechanism to drive significant exchange between the two waterbodies. While previous modeling studies (Young et al. 2011; Gudimov et al. 2012) have
hinted at the importance of flushing time scales to the cycling of nutrients in Lake Simcoe, no previous research investigated any details of flushing. More specifically, no studies have combined velocity measurements with high-resolution spatial coverage of temperature around an embayment to fully monitor the lateral changes in thermocline tilt that are likely caused by rotational influences. Our study thus aims to determine how important these temporal changes of velocity and thermocline are in pumping water and in driving a residual circulation. We hypothesize that fluctuations of the internal wave field in Kempenfelt Bay produce a “bellows” effect resulting in significant volumetric fluxes that control the exchange dynamics of the embayment. As the Burger number for this large embayment is close to unity, indicating internal wave dynamics are expected to be influenced by the Earth’s rotation, and it has a similar geometry to the Petit Lac of Lake Geneva, it is proposed that there may be a signature of internal Kelvin-type waves in the bay, which should result in a net cyclonic circulation that would act as a secondary exchange mechanism in this sensitive embayment. Our study used a detailed array of instruments to make field observations in 2014, 2015, and 2016 of conductivity, velocity, and thermal structure, which allowed us to observe the lateral gradients of velocity and both longitudinal and lateral gradients of temperature and conductivity. We used these data to investigate the relationship between the internal wave field and the exchange of water masses with the main basin, as well as to determine the impacts of the Coriolis force upon internal wave pumping in this long and deep coastal embayment of Lake Simcoe.

**Methods**

**Site description**

The deep (42 m maximum), long (15 km), and narrow (≈ 2 km) Kempenfelt Bay on the western side of Lake Simcoe is characteristic of many of the deep embayments in the Laurentian Great Lakes. Lake Simcoe is a large lake of surface area 722 km² in southern Ontario, Canada, which has been influenced by European-style settlement and subsequent development for
more than two centuries resulting in persistent water quality issues (North et al. 2013). Due to concerns regarding the influence of eutrophication on the valuable coldwater fishery (Winter et al. 2007), Kempenfelt Bay has been part of an annual monitoring program since 1980 (see site K42 in Fig. 1) providing long-term trends of DO, conductivity, and details of stratification useful for investigating the exchange dynamics between the embayment and main basin. DO is also used as a water quality indicator by government agencies tasked with restoring lake health. The addition of nutrients, especially phosphorus as a result of deforestation, agriculture, and urban development, is believed to be the primary cause of reduced water quality in the lake, leading to increased algal growth, reduced DO, and the degradation of coldwater species habitat (Evans et al. 1996; LSPP 2009; North et al. 2013). Coldwater fishes, such as lake trout (Salvelinus namaycush), lake whitefish (Coregonus clupeaformis), and cisco (Coregonus artedi), have thermal preferences of < 10°C–14°C, limiting their preferred thermal habitat to below the summer thermocline (Coutant 1977; Christie and Regier 1988). In addition, coldwater fish recruitment is optimal at DO levels > 7 mg L⁻¹, making these populations susceptible to collapse due to eutrophication and end-of-summer hypoxia in deep waters (Winter et al. 2007). As a result, spatial and temporal variability of thermocline depth could influence fish habitat usage, as well as determining the pumping rates of waters between the bay and the main lake. Moreover, concentrations of sodium chloride, a byproduct of winter road salting activities, have been steadily increasing with chloride concentrations at the lake’s outflow increasing more than threefold between 1971 and 2007, further degrading water quality (Winter et al. 2011).

**Observation campaign**

To determine the role of thermocline movements in setting the flushing rate of Kempenfelt Bay, field measurements of water temperature, DO, water currents, and conductivity were taken during the summer-stratified period in 2014, 2015, and 2016. This article focuses on the 2015 field campaign. While the 2014 and 2016 campaigns were similar in design and intent, they differed in the amount and type of equipment and deployment durations (see Supporting Information Table S1 for details), so provide interannual context for the internal wave structure (period and amplitude, as well as stratification). For all 3 yr, air temperature and wind data were collected from the Environment and Climate Change Canada weather Buoy (Sta. 45151) located in the northern part of the main Lake Simcoe basin (44°30′0″N 79°22′12″W), approximately 15 km from Kempenfelt Bay (Fig. 1).

Eight thermistor strings were deployed in 2015 along the perimeter of Kempenfelt Bay to observe the temporal and spatial variability in thermocline movements (Fig. 1; Supporting Information Table S1). Deploying four strings each along the north and south shores allowed for the observation of longitudinal and lateral dynamics of the internal wave field within the embayment. Strings 1 through 6 were comprised of 15 HOBO thermistors spaced at 1 m intervals through the mid-depths (≈ 12–24 m) where the thermocline was expected to reside, and 2 m intervals above this zone (≈ 6–12 m) to complete the water column temperature profile. Strings 7 and 8 were equipped with SeaBird loggers and placed beside the north and south acoustic Doppler current profilers (ADCPs; ≈ 130 m and 200 m away, respectively) to provide temperature data to facilitate water current analyses. Six of the thermistors on String 3 (at 3 m intervals) were replaced with PME MiniDOT loggers to record DO as well as temperature. The top instrument position of Strings 1 through 6 (nominal depth ≈ 6 m) was reserved for a HOBO pressure logger, which recorded the pressure (used for depth calculations assuming hydrostatic conditions) and temperature. Atmospheric pressure changes were removed with data from an additional HOBO pressure logger placed nearby on shore. Density was calculated from thermistor temperature records using the nonlinear equation of state following Chen and Millero (1986). The measured conductivity gradients were very weak and had negligible influence upon density during the strong thermal stratification; therefore, we ignored salinity when calculating water density. Thermocline depth was calculated as the first moment of the water density field following Patterson et al. (1984) as 

$$z_{\text{thermocline}} = \int z \cdot \rho(z) dz / \int \rho(z) dz,$$

where $z$ is water depth and $\rho(z)$ is the corresponding water density.

To determine longitudinal and lateral variability in water currents flowing in and out of the bay, two ADCPs were deployed (one each on the north and south shores) in Kempenfelt Bay for 16 weeks during the summer-stratified period in 2015 (Fig. 1, Supporting Information Table S1). To achieve high-spatial resolution, both ADCPs measured water currents in three directions (east, north, up) in 1 m bins through the entire water column. The ADCP units were placed on the lakebed at ≈ 24 m depth in gimbaled frames looking upward.

To investigate the influence of wind forcing on the internal wave field, we calculated the Wedderburn number, $W$, which is the ratio of the baroclinic restoring force to wind stress. Following Thompson and Imberger (1980) and Imberger and Hamblin (1982), $W = \Omega^2 / g U^2$, where $g'$ is the reduced gravity in m s⁻² ($g' = g \left(1 - \frac{\rho_l}{\rho_w}\right)$), $h_1$ is the thickness of the upper mixed layer (m), $L$ is the basin length scale (m), and $u_*$ is the wind shear stress (m s⁻¹). $U_{10} = \sqrt{\left(\rho_w / \rho_a\right) C_d U_{10}^2 / 10}$, where $\rho_a$ is the density of air (1.225 kg m⁻³) and water (mixed upper layer), respectively, $C_d$ is the drag coefficient between air and the water surface ($\approx 1.3 \times 10^{-3}$), and $U_{10}$ is the wind speed measured 10 m above the water surface (m s⁻¹).

To characterize the internal wave field, estimates of the periods of basin-scale internal waves were approximated using Merian’s formula (Bengtsson et al. 2012):

$$T_n = \frac{2L}{u_*} \left/ \sqrt{n} \right.$$

(2)
where \( L \) is the horizontal length scale, \( n \) is the horizontal mode number, and the internal wave phase speed, \( c_i = 0.22 \, \text{m s}^{-1} \), was obtained by solving the linear two-layer shallow water equation, \( c_i = \sqrt{\frac{g}{h} \frac{1}{H}} \) where \( H = h_1 h_2/(h_1 + h_2) \) is the equivalent depth while \( h_1 \) and \( h_2 \) are the thicknesses of layers 1 and 2, respectively (Massel 2015). Mean thermocline depth \( (h_1 = 16 \, \text{m}) \) was obtained from temporal averaging of the thermocline depth (Day-Of-Year (DOY) 217–263) for all strings, while \( h_2 = H - h_1 \), where \( H = 22 \, \text{m} \) (mean depth of the central basin in Lake Simcoe including Kempenfelt Bay). Mean epilimnetic and hypolimnetic water temperatures were depth-averaged (based on calculated thermocline depth) and temporally averaged (DOY 217–263). Densities were then calculated from the equation of state.

Conductivity-temperature-depth (CTD) measurements were taken to observe how a passive tracer (salt) was advected through Kempenfelt Bay. On 22 September 2015 (DOY 265), 16 CTD profiles (Fig. 1, Supporting Information Table S1) were taken to map the spatial variability of conductivity, a proxy for salt, in Kempenfelt Bay. A salt balance approach like the one utilized by Pritchard (1960) is common in marine systems to estimate residence time in bays and estuaries. Similar to other studies in the freshwater environment (McNamara et al. 1997; Gikuma-Njuru et al. 2018), we employed specific conductance (SC) in lieu of salinity as a passive tracer to observe temporally averaged circulation patterns of waters between Kempenfelt Bay and the main basin of Lake Simcoe. Salt (i.e., SC) is a useful tracer due to its conservative nature and continual input into Lake Simcoe. Salt is primarily applied in the winter as a road deicer, with approximately 100,000 tonnes applied to paved surfaces in the Lake Simcoe watershed each year (LSRCA 2016). While salinity peaks are typically observed in the winter and spring when meltwater containing road salt flows into tributaries via storm water pipes and overland flow, a significant portion can be retained in the watershed, with the potential to enter the lake throughout the year; for example, a chloride (Cl⁻) retention rate of approximately 75% was calculated for Lovers Creek, which runs through Barrie (Oswald et al. 2019). Lovers Creek has mean annual Cl⁻ concentrations in excess of 100 mg L⁻¹ (Winter et al. 2011), likely due in part to its proximity to the large urban center of Barrie (population of ~ 150,000, Statistics Canada 2017). Lake Simcoe Region Conservation Authority monitors chloride concentration in Lovers Creek and conductivity in four other large tributaries entering Kempenfelt Bay (Fig. 1), as well as three sites in Lake Simcoe’s main basin. The monitored tributaries had much higher conductivities (mean September 2015 SC of 1100 \( \mu \text{S cm}^{-1} \)) than either the main basin (mean SC of 402 \( \mu \text{S cm}^{-1} \) on 10 August 2015 [DOY 222]) or Kempenfelt Bay (depth-averaged and spatially averaged SC of 408 \( \mu \text{S cm}^{-1} \) from 22 September 2015 [DOY 265] CTD measurements). The large difference between input and receiving body conductivities allowed us to use SC as a passive tracer. With tributary loading occurring primarily at the end of the embayment (see Fig. 1), conductivity measurements were able to shed light on the temporally averaged circulation patterns in Kempenfelt Bay. If there was any residual circulation within the bay, we would expect a difference in conductivity between north and south shores. A counterclockwise circulation would have fresher main basin water advecting into Kempenfelt Bay along the north shore, mix with saltier embayment water (due to tributary loading) as it reaches the end, and advect out along the south shore. This would result in slightly lower conductivities along the north shore with slightly elevated conductivities along the south shore. If there were just diffusive transport within the bay, then there would be a gradient of conductivity from the head of bay to the open waters of Lake Simcoe.

The potential presence of persistent asymmetries in the direction and/or magnitude of water currents on either side of Kempenfelt Bay could result in a residual circulation that affects exchange dynamics with the main basin. In addition to SC data, ADCP observations provided direct information regarding velocities along the north and south shores that help us understand circulation patterns within Kempenfelt Bay. Temporally averaging the ADCP data for each meter of water depth on both sides of the embayment allowed us to observe any net circulation. This analysis was augmented by plotting velocity vectors tip to tail, creating progressive vector diagrams (PVDs; time-step averaged epilimnetic velocity multiplied by time step length for 10 consecutive 98 h periods), which are useful tools for investigating the potential flow path of a water parcel. Potential mean excursion length scales were estimated by averaging several PVDs for both north and south ADCPs. By using ADCP data collected at only two locations to reconstruct the Eulerian flow field, and assuming spatially homogenous water currents throughout the embayment, PVDs depicted fictitious excursion paths, i.e., the velocity vector was calculated at the ADCP but plotted at the tip of the previous vector. Nevertheless, the PVDs were instructive in determining the potential distance and direction a water parcel could travel over one wave period.

**Flushing rate analysis technique**

The rate at which water was exchanged between Kempenfelt Bay and the main body of Lake Simcoe by vertical movements of the thermocline was estimated by analogy to the partial flushing in an estuary due to tidal pumping; as the thermocline moves vertically, surface water is drawn into the bay as the thermocline falls, while water is being pushed out of the bay below the thermocline, and vice versa as the thermocline rises. A similar analysis was carried out by Laval et al. (2008), demonstrating how exchange flow between basins in a fjord-type lake was controlled by vertical movements of the thermocline.

We modified the tidal prism concept, using idealized geometry and mean thermocline depths, to investigate the exchange rate of epilimnetic waters in Kempenfelt Bay due to thermocline fluctuations. The flushing rate, FR, represents the volume of water, expressed as a fraction of mean epilimnetic volume, which leaves and re-enters the embayment per unit time (d⁻¹). Mean flushing time is then given by \( t_f = 1/FR \), with FR calculated as:
where $V_{\text{epi}}$ is the mean epilimnetic volume (m$^3$), $V_{\text{epi}}(t)$ is the epilimnetic volume (m$^3$) at time $t$, and the 2 in the denominator accounts for water having to both enter and exit to be considered exchanged. The change in epilimnetic volume can be calculated using the formula:

$$\frac{\partial V_{\text{epi}}(t)}{\partial t} = L \times \frac{\partial A_{\text{CSepi}}(t)}{\partial t}$$

(4)

where $L$ is the length of Kempenfelt Bay (15 km), $A_{\text{CSepi}}(t) = \frac{(w + w_{\text{thermo}})}{2} \times z_{\text{thermo}}$ is the cross-sectional area of the epilimnion (m$^2$), and $w$ is the width of Kempenfelt Bay (m) at the surface ($z = 0$) and at the mean thermocline depth, $z_{\text{thermo}}$. Because our formula does not include a return flow factor and does not account for possible short-circuiting, FR represents an upper limit on the flushing rate resulting from vertical thermocline oscillations.

Changes in epilimnetic volume, $V_{\text{epi}}$, with time due to vertical thermocline fluctuations (Eq. 4) result in horizontal current velocities as the water is squeezed out of, or drawn into, the embayment. The associated along-shore epilimnetic current velocities, $u_{\text{epi}}$, were determined by dividing the volume flux by the vertical cross-sectional area $A_{\text{CSepi}}$ of the epilimnion (through which the water flows), as per the equation:

$$u_{\text{epi}} = \frac{1}{A_{\text{CSepi}}} \times \frac{\partial V_{\text{epi}}(t)}{\partial t}.$$

(5)

Because $u_{\text{epi}}$ is a basin-width average, it explicitly neglects any possible differences between the north and south shores. We compared the theoretical epilimnetic current velocities due to thermocline movements (Eq. 5) to direct measurements of horizontally and vertically averaged epilimnetic velocities obtained from ADCP observations to determine the utility of Eq. 3 and its underlying assumptions. To isolate the influence of dominant internal waves ($T = 49$ and 98 h), both observed and inferred velocity data sets were low-pass filtered with a cut off of 12 h. This removes small-amplitude, high-frequency thermocline fluctuations that are not expected to drive exchange due to the short water parcel excursion lengths, as well as effects of transverse internal waves that would not drive inter-basin exchange (transverse mode 1 internal seiche period for Kempenfelt Bay was calculated to be 5 h from Eq. 2).

Results

A pronounced thermal stratification was observed over the entire 2015 observation campaign (DOY 201–280) revealing the presence of large amplitude internal waves (Fig. 2; Supporting Information Fig. S1). For the remainder of the results, unless otherwise noted, we focus on the period of 05 August 2015–20 September 2015 (DOY 217–263) when we had ADCP data. During this period, mean near-surface temperatures (nominal depth of $\approx 4$ m) were 21$^\circ$C whereas mean benthic temperatures (nominal depth of $\approx 22$ m) were 9$^\circ$C. Thermocline depth averaged $\approx$ 16 m with oscillations having typical amplitudes on the order of meters (maximum of $\approx$ 10 m on DOY 256–257), highlighting the ubiquitous nature of large amplitude internal waves in Kempenfelt Bay (Fig. 2d). Similar thermocline movements were also seen in 2014 and 2016 (Supporting Information Fig. S1).

Winds blew predominantly from the west (SW, W, NW) with speeds typically between 2 and 8 m s$^{-1}$ (mean of 4.1 m s$^{-1}$) (Figs. 1, 2b,c). Strong, sustained winds were the primary driver for the setup of large thermocline tilts across Lake Simcoe. The strongest internal waves in Figs. 2, 3 are related to upwelling events due to wind impulses, which subsequently oscillate over several days before another strong wind event resets the thermocline tilt. The Wedderburn number was calculated for decomposed winds and plotted in Fig. 3 with thermocline deflection from the mean depth (4-week moving average, chosen to be long enough to average out the influence of individual internal wave events but short enough to reflect longer timescale trends such as seasonal deepening of the thermocline). Strong wind events with $|1/W| > 1/3$ (Shintani et al. 2010) were frequently accompanied by large vertical movements of the thermocline, exposing the importance of wind forcing in energizing the internal wave field (Fig. 3). Not surprisingly, strong westerly wind events across Lake Simcoe often resulted in an upwelling thermocline in Kempenfelt Bay, particularly evident around DOY 203, 212, 218, 225, and 257 (Fig. 3). Free oscillations of the internal wave occurred upon the cessation of strong wind events, with periods dictated by basin geometry and stratification; for example, during DOY 226–232, the thermocline oscillated with a period of approximately 98 h in the absence of any strong wind events (Fig. 3). We expect that velocity of only the top several meters of the water column would be directly influenced by wind (Choi et al. 2015). Although the top few meters of the water column in the ADCP data were removed due to side-lobe interference with the surface (Fig. 2e,f), this influence was clearly observed from DOY 236 to 239, when strong westerly winds drove fast eastward near-surface currents, and DOY 247–248, when the strong easterly winds resulted in westward near-surface currents. Air temperature during the observation campaign was typically between 15$^\circ$C and 25$^\circ$C, with diurnal fluctuations of approximately 5$^\circ$C (Fig. 2a).

Significant oscillating along-shore currents were measured by north and south shore ADCPs. The along-shore component of velocity ($u$) was on the order of 10 cm s$^{-1}$ (Fig. 2e,f), whereas across-shore currents ($v$) were an order of magnitude smaller (not shown). Currents typically reversed across the metalimnion, so that baroclinic flow was reminiscent of a two-layer system (Fig. 2e,f). Periodic current reversals in both the epilimnion and hypolimnion that are sustained over prolonged
periods (days) suggest significant exchange of embayment and main basin waters (Fig. 2e,f).

DO, measured at String 3 on the north shore, decreased during the summer of 2015 as the stratified period progressed, developing a negative heterograde profile with oxygen minimum in the metalimnion (Fig. 2g). While this phenomenon has not, to our knowledge, been previously reported in Lake Simcoe, it is not unusual in stratified lakes. It was likely caused by an elevated respiration rate of organic matter through the metalimnion that built up as a result of the decreased settling rate due to the increased vertical density gradient through the thermocline (Wetzel 2001). The depth of the hypoxic layer fluctuated with the internal wave field, resulting in intermittent vertical excursions into shallower and deeper waters, which could alter the habitat of coldwater fishes.

**Internal wave periods**

Water exchange due to internal wave pumping was determined by both the amplitude and frequency of thermocline movements. To determine dominant periods, thermocline depth data were detrended and subsequently low-pass filtered (cut-off period of 0.5 h) to remove small-amplitude, high-frequency fluctuations in thermocline depth arising from localized phenomena that do not contribute to exchange dynamics. Subsequent spectral analysis of thermocline depth revealed dominant internal wave periods in Kempenfelt Bay at approximately 98, 49, 17.3, and 3 h (Fig. 4c). The broad peak in spectral density at approximately 17.3 h likely represents the inertial period, $T_i = \frac{2\pi}{f} = 17.1$ h. The longer period peaks of 98 and 49 h are likely seiches controlled by the larger size of the main basin of Lake Simcoe. Similar internal wave regimes have been found in comparable lakes such as Upper Lake Constance (Appt et al. 2004), Lake Geneva (Bouffard and Lemmin 2013), Lake Champlain (Hunkins et al. 2013), Lake Zurich (Horn et al. 1986), and Kootenay Lake (Wiegand and Carmack 1986). Using length scales, measured at the mean thermocline depth (16 m), of 20 km for the main basin and 35 km for the main basin including Kempenfelt Bay, Merian’s formula (Eq. 2) yielded periods of 50 h and 88 h, respectively, consistent with the 49 and 98 h periods observed in the spectral plots. These results agreed with Bouffard and Boegman’s (2011, 2012) basin-scale (Lake Simcoe and Kempenfelt Bay) internal Kelvin wave period of ≈ 90 h during a similar stratified period (July–September 2008). The broad peak around 3 h is likely related to the transverse internal seiche period in the ≈ 2 km wide Kempenfelt Bay where $2L/c_i = 5$ h.

The peaks at 1 h and 1.4 h (not labeled) in the thermocline spectral analysis, which were also present in the spectral analyses

![Fig. 2. Physical parameters for 2015. (a) Air temperature (°C), (b) direction wind is coming from (azimuthal degrees), (c) wind speed (m s⁻¹), (d) water temperature (°C) at S3, (e, f) along-shore current (u) velocities (m s⁻¹) at north and south ADCPs, respectively, showing eastward (positive; red) and westward (negative; blue) values, and (g) DO (mg L⁻¹) at S3. The superimposed black line shows the thermocline calculated at S3 for (d, e, g) and S4 for (f).](image-url)
of water current and pressure (Fig. 4b,d), were consistent with a surface seiche in the open-mouthed Kempenfelt Bay, and a basin-scale surface seiche in the Lake Simcoe-Kempenfelt Bay system, respectively. Following Rabinovich (2009), the modified Merian’s formula (Eq. 2) for the lowest mode surface seiche in a rectangular open-ended basin \((n = 0)\) with a rectangular bed shape is

\[ T = \frac{2 \times 2L}{\sqrt{gH}}. \]

Solved for Kempenfelt Bay \((L = 15 \text{ km and } H = 25 \text{ m})\), \(T = 1 \text{ h}\). Using Merian’s formula for a surface seiche, \(T_{\text{surface}} = \frac{2L}{\sqrt{gH}}\) (where \(L = 35 \text{ km and } H = 17 \text{ m}\) is the mean depth of Lake Simcoe) predicts a period of 1.5 h, consistent with the 1.4 h signal observed in the spectral plots.

A spectral analysis of the depth-averaged epilimnetic along-shore velocities indicates dominant wave periods of 98, 49, and 1 h (Fig. 4d). These peaks were consistent with the thermocline spectral analysis, exposing the coupled response between thermocline movement and velocities. We note that the \(\approx 2.9–3.6 \text{ h}\) period that was interpreted as a transverse mode was not seen in the across-shore epilimnetic current \((v)\) spectral analysis (not shown); this is likely because velocities associated with this mode would go to zero at the boundaries where the ADCPs were located. We also note that the inertial period \((T_i = 17.1 \text{ h})\) was not seen strongly in this record, likely because a Poincaré-type wave has maximum velocity in the center of basins, whereas the velocity goes to zero at the boundaries (Csanady 1968). Similar internal Poincaré wave signatures were observed in the southern basin of Lake Michigan by Ahmed et al. (2013) and in Lake Superior by Austin (2013).

In addition to the vertical mode 1 response, there were a couple occurrences that had the signature of a mode 2 response whereby the metalimnion expanded and subsequently recompressed starting around DOY 226 and again around DOY 258 (Fig. 2d). The period of the V2H1 mode was found to be approximately 132 h following Munnich et al. (1992) and using estimates of \(h_1 = 12 \text{ m, } h_2 = 7.5 \text{ m, and } h_3 = 2.5 \text{ m}\) for the layer depths. Because of the limited number of occurrences, it is not surprising that the mode 2 wave did not appear in the power spectrum density plots. The mode 2 wave is likely another driver of transport and exchange between Kempenfelt Bay and Lake Simcoe, a detailed analysis of which was not attempted in this study.

Spatial structure of internal waves
The internal wave field in Kempenfelt Bay consisted of a primary vertical oscillation structure with a secondary lateral tilt superimposed; this is best visualized by analyzing the internal wave field at discrete times (Figs. 5, 6). Using an internal wave
phase speed from Eq. 2 of 0.22 m s$^{-1}$ and $L = 2$ km in Eq. 1 yielded a Burger number of $S_i = 1$. For Kempenfelt Bay, with a Burger number on the order of unity, internal wave dynamics in Kempenfelt Bay are expected to be influenced by the Earth’s rotation, which would manifest in the internal wave field. Similarly, Priet-Mahéo et al. (2019) observed internal Kelvin waves in the long (27 km) and narrow (2 km) arctic Lake Lagårðjót (65°14′N, $S_i = O(10^{-1})$ or O(1)) resulting in counterclockwise propagating temperature disturbances that decayed offshore. The influence of the Coriolis force upon the secondary thermocline tilt can be seen by looking at successive panels of Fig. 5; taking the starting point ($t = 0$; Panel I) as the trough of the wave and progressing through a full wave period (proceeding at quarter period intervals clockwise through panels II–IV), it can be seen that the predominant feature was a cohesively rising and falling internal wave throughout the entire embayment, with significant implications for pumping water between the basins. This was supported by the field data ($T = 98$ h) with a deep thermocline at $t = 0$ (close to the trough phase) compared to the predominantly shallow thermocline when the internal wave was near the crest phase ($t = T/2$) (Fig. 6). During the first (panel II; $t = T/4$) and third (panel IV; $t = 3T/4$) quarter periods, the internal wave was at an intermediate depth. The picture of this was slightly obscured due to a transverse thermocline tilt that was superimposed on the internal wave that resulted from Coriolis forces curling the water to the right in the flow direction. As water flowed out above the rising thermocline, it curled to the right (south) depressing the thermocline on that side. At the same time, hypolimnetic water flowing into the embayment was curling to the north (right in the flow direction), accumulating below the thermocline on the north shore further contributing to the lateral tilt. This effect manifested in the form of asymmetrical current magnitudes (illustrated through arrow size in Fig. 5, panel II), and lateral tilts reaching over 5 m (data not shown) across the embayment. The process reversed during the second half of the wave period as the thermocline dropped from crest to trough (Fig. 5, panel IV).

**Water currents**

Velocities within the water column were tightly coupled to dynamics of thermocline movements (Figs. 2e,f, 4c,d). As the thermocline was rising in Kempenfelt Bay, epilimnetic waters above the thermocline were squeezed out of the embayment (eastward) into the main basin, while hypolimnetic waters...
were drawn in (westward) (e.g., DOY 256–257 in Fig. 2 corresponding to panel II of Fig. 5). As the internal wave propagated around Lake Simcoe and the thermocline in Kempenfelt Bay dropped, water must have been drawn into the embayment above the thermocline from the main basin to satisfy mass and volume conservation (provided there was no change in surface level). This was clearly observed on DOY 258–259 (Fig. 2e,f), when epilimnetic water masses above the sinking thermocline flowed predominantly westward into the embayment (panel IV of Fig. 5). The connection between vertical thermocline oscillations and horizontal currents was further established through the matching spectral peaks (Fig. 4c,d), suggesting they were coupled. The primary structure of the rising and falling internal wave in Kempenfelt Bay, as it propagates around Lake Simcoe, thus results in a bellows-like effect, continuously pumping water into and out of the embayment.

When plotted together in Fig. 7, good agreement was found between measured and predicted spatially averaged epilimnetic
velocities in both magnitude and direction, especially over timescales corresponding to the dominant internal wave periods ($T = 49$ and $98$ h). Plotted against each other (not shown), the observed (ADCP measurements) and predicted (derived from thermocline movements) spatially averaged epilimnetic current velocities exhibit a strong correlation ($R^2 = 0.65$).

Residual circulation

The analysis of temporally averaged water currents above the thermocline identified predominantly westward flows along the north shore and eastward flows along the south shore, highlighting a counterclockwise residual circulation in the epilimnion of Kempenfelt Bay (Fig. 8b). The simultaneous observations of north and south shore mean epilimnetic currents also strongly suggest a counterclockwise flow, with the majority of observations (56%) westward along the north shore and eastward along the south (Fig. 8a). For 42% of the observations, the north and south shore currents were flowing in the same direction, but often with differing magnitudes resulting in flow asymmetries across the embayment (Fig. 8a quadrants II and III: observations above 1:1 line result in counterclockwise flow while those below correspond to clockwise flow). This residual circulation results in a persistent exchange of water between Kempenfelt Bay and the main basin. These observations can be interpreted as large-amplitude internal waves being influenced and deflected to the right in the direction of travel by the Earth’s rotation within the embayment.

Conductivity measurements in Kempenfelt Bay on DOY 265 exhibited a temporally averaged spatial pattern reflective of a counterclockwise residual circulation (Fig. 9). Depth-averaged (over the top 15 m) SC was persistently higher near the western tip of Kempenfelt Bay and along the south shore (Fig. 9). During the two preceding weeks, general westward flows along the north shore and eastward along the south (Fig. 10, Supporting Information Fig. S2) facilitated the conductivity advection pattern observed on DOY 265. To a first approximation, mass...
balance calculations (following Wells and Sealock 2009) suggest tributary loading alone accounted for an increase in embayment SC of around 1 \( \mu \text{S cm}^{-1} \), which was of the same order of magnitude as observed laterally across Kempenfelt Bay. These findings are consistent with a counterclockwise circulation; fresher main basin water entered along the north shore, while saltier embayment water flowed out along the south shore.

PVDs corroborate our counterclockwise residual circulation assertion by highlighting the asymmetrical currents across Kempenfelt Bay (Fig. 10). The PVDs had an average maximum excursion length for the north ADCP of 11.7 ± 6.0 km and for the south ADCP of 8.8 ± 3.8 km. In agreement with the residual circulation analysis, the PVDs illustrated a strong tendency for predominantly westward flows on the north side of the embayment, and eastward flows on the south side (Fig. 10), which were also consistent with the idea that the Coriolis force acting on internal waves drives a residual counterclockwise circulation around Kempenfelt Bay.

**Estimation of flushing timescales**

Due to the sporadic nature of the wind forcing, flushing rates varied dynamically with time. To get a representative range of flushing time scales, volumetric exchanges were calculated over 98 h subsets (\( n = 17, \text{DOY 201–270} \)) and mean flushing rates were subsequently calculated with Eq. 3, resulting in a mean seasonal flushing time of \( t_f = 17 \pm 6 \text{d} \). This indicates that approximately every 17 d, a volume of water equal to the mean epilimnetic volume flowed into and out of the epilimnion of Kempenfelt Bay as a result of thermocline fluctuations. Since Eq. 3 does not include a return flow factor, it is likely to overestimate flushing rate, as water leaving on the ebb flow can re-enter on the subsequent flood flow (for more details, see “Limitations of exchange estimates” section). Relatively long water parcel excursion length scales (8.8–11.7 km) suggest that a significant fraction of water could leave Kempenfelt Bay and mix with main basin water during each 98 h wave period. While limitations of the PVD method make it difficult to conclusively quantify water parcel excursion lengths in Kempenfelt Bay, it qualitatively indicates relatively long excursion lengths, suggesting significant exchange between the embayment and main basin, similar to quantitative observations of flushing the Petit Lac of Lake Geneva (Umlauf and Lemmin 2005).

An estimate of exchange rate based on residual circulation provides an upper range for flushing time. We first made a few simplifying assumptions: (1) Thermocline was horizontal and calculated independently for north and south sides, based on

**Fig. 7.** Mean along-shore epilimnetic current velocities (\( u \)) measured with ADCPs in green (mean from north and south shore ADCPs) and predicted (blue line) based on vertical thermocline fluctuations (spatial mean of all available strings, low-pass filtered with a cut-off period of 6 h). Positive values are eastward, negative are westward. Coefficient of determination (\( R^2 \)) for ADCP vs. thermocline-derived epilimnetic current velocities is 0.65.
String 7 and 8 temperature data; (2) epilimnetic volumes were based on idealized geometry (depicted in Fig. 5 panel III); and (3) current velocity was maximum at the shore (where ADCPs were placed) and decreased linearly to zero at the midpoint of the embayment. This was simplified from the actual structure of internal Kelvin-type waves, where currents decay exponentially away from the coast to zero at a distance of one Rossby radius. Using vertically and temporally averaged epilimnetic velocities, flushing times ($t_f = V/Q$) of 66 d and 100 d (north and south shore, respectively) were calculated. Using thermocline-derived pumping and residual circulation to subtend an estimate of exchange rate range suggests that the flushing time of Kempenfelt Bay was on the order of a couple weeks to a few months. Both upper and lower bound estimates were significantly shorter than flushing time estimates based on tributary inputs alone, which were on the order of decades (using mean tributary flow data [1998–2004] from Scott et al. 2006 for Lovers Creek).

**Discussion**

Sustained winds over the surface of Lake Simcoe energized large amplitude internal waves along the thermocline of the lake's interior. These internal waves were influenced by the Earth's rotation resulting in Kelvin-type waves propagating counterclockwise with the lake shore on the right in the direction of travel. As they propagated into and out of Kempenfelt Bay, they appeared to act as a bellow, pumping water into and out of the embayment, both above and below the thermocline. Owing to the strong thermal gradient and flow reversal across the metalimnion, the thermocline acted as an interface separating the epilimnion from the hypolimnion. As the thermocline in Kempenfelt Bay was rising, water was horizontally squeezed out of the epilimnion and drawn into the hypolimnion from the main basin, given that there is minimal vertical flux across the thermocline (Chowdhury et al. 2015), and the reverse occurred as the thermocline was sinking. Additionally, geostrophic forces acting on the water masses within Kempenfelt Bay drove a secondary residual circulation furthering exchange processes between the two basins. The energetic internal wave field, a combination of both forced and free oscillations, was a fundamental driver of exchange and thus could be central in controlling the water quality of Kempenfelt Bay.

The agreement in the averaged epilimnetic flow direction between temperature and velocity data in Fig. 7 provides...
confidence to our bellows hypothesis; vertical fluctuations in
the thermocline are coupled with horizontal currents, with a
rising thermocline pumping water out of the epilimnion in an
easterly direction, and vice versa for a sinking thermocline.
Agreement in magnitude suggests that the horizontal velocity
field can, to a first-order approximation, be explained by the bel-
lows hypothesis alone. The good agreement between spatially
averaged observed and derived current velocities suggests that
the observed currents in Kempenfelt Bay were driven, in large
part, by thermocline fluctuations with periods on the order of
days, indicating thermocline dynamics were an important
mechanism for pumping water into and out of the embayment.
While averaging across the north and south shore data sets
allows us to compare net observed and inferred fluxes (via spa-
tially averaged velocities), it neglects across-bay variability,
obscuring any residual circulation present in the embayment.

Our mechanisms for driving circulation and flushing are quite
different from assumptions made in two recent theoretical model-
ing papers of Kempenfelt Bay. For instance, Gudimov et al. (2012)
employed an inverse modeling approach to calculate an a
posteriori flushing time estimate of $345 \pm 74$ d based on nutrient
loading budgets. This estimate helps close the phosphorus budget,
but does not consider any physical processes, such as thermocline
movements, and thus is unlikely to represent the hydrodynamics
present in the embayment. Gudimov et al. (2015) improved on
Gudimov et al. (2012) by incorporating bidirectional flow between
model boxes, calculating flux into Kempenfelt Bay as the balance
between net flux, taken from Gudimov et al. (2012) estimates,
and inflow into Kempenfelt Bay from the catchment. Because net
flux was again based on nutrient budgets without incorporating
hydrodynamics (due to data limitations), there was no physical
basis for their flushing time estimates.

**Variability of exchange estimates**
Exchange rates were dynamic across scales ranging from days
to seasonally. Averaging over 98 h periods (the dominant period
for flushing considerations, $n = 17$), the mean flushing rate fluc-
tuated between 0.03 and 0.11 d$^{-1}$ ($t_f = 9–33$ d) in 2015.
Interannual variability in exchange rates, due in part to climatic factors that controlled stratification and variability in wind forcing dynamics, was also high: seasonally averaged exchange rates varied by up to a factor of 2 over the 3 yr investigated (12 d, 17 d, and 9 d for 2014, 2015, and 2016, respectively; Supporting Information Fig. S3). Increasing stratification, while holding all other variables constant, results in smaller amplitude and shorter period internal waves, which have opposing influences on flushing rates. Their combined effect, however, is to decrease exchange as stratification strengthens. Other factors that influence exchange dynamics such as thermocline depth, and basin length and width at the thermocline depth would vary in tandem with changes in stratification, resulting in basin-specific responses. While the degree of stratification strongly influences exchange rates, other factors such as the wind-forcing regime are also important. For example, the flushing rate in 2016 was approximately twice that of 2015 (Supporting Information Fig. S3), despite having a stronger stratification (Supporting Information Fig. S1). This could be attributed to the more energetic wind climate in 2016, when mean summer (July, August, and September) wind speeds were 8% faster than in 2015.

Hypolimnion exchange rates

Using the observed correlation between velocities and thermocline movements in the epilimnion, we infer what the flushing time scales should be for the hypolimnion. While our experimental design did not allow for direct observations of velocities throughout the hypolimnion, the theoretical framework we developed to predict epilimnetic flushing rates is equally valid for the hypolimnion. Vertical thermocline oscillations are expected to result in equal but opposite volumetric fluxes in the epilimnion and hypolimnion, provided the surface-water level remains constant, while current velocities and flushing rates depend on the vertical cross-sectional area and volume of the hypolimnion. Employing the same idealized basin geometry and thermocline depth data used in the epilimnetic calculations yields a seasonally averaged hypolimnetic flushing time of 13.5 ± 5 d for 2015. This is a good match with the predicted value based on a mean hypolimnetic-to-epilimnetic volume ratio (4.1 x 10^8 m^3/5.1 x 10^8 m^3 = 0.8 and 13.5 d/17 d = 0.8). Furthermore, this suggests that global exchange rates and flushing times for Kempenfelt Bay were similar to those calculated for the epilimnion, while erring on the conservative side.

Limitations of exchange estimates

The seasonally averaged flushing time signifies that a volume of water equal to that of the epilimnion flowed into and out of Kempenfelt Bay approximately every 17 d. It does not, however, speak to how often all the epilimnetic water in the embayment was exchanged for “fresh” main basin water, as some of the water that leaves on the ebb flow could return on the subsequent flood flow. In an effort to estimate the relative exchange induced by internal waves in Kempenfelt Bay, PVDs depicted the theoretical excursion paths of water parcels over the course of one wave period (T = 98 h) in Kempenfelt Bay (Fig. 10). Based on mean epilimnetic flow rates measured over 10 consecutive periods, PVDs revealed a mean (across north [11.7 km] and south [8.8 km] ADCPs) maximum excursion length of 10.3 ± 5.1 km. This represents length scales of

![Fig. 10. Progressive vector diagrams for both the north and south ADCPs, based on mean epilimnetic flow rates (below wind-influenced zone). PVDs are for consecutive 98 h periods, starting at the beginning of the ADCP observation period (DOY 217.7).](image-url)
approximately 1/2 to 2/3 of the embayment length. Calculating excursion lengths from PVDs requires us to apply currents measured at the ADCPs homogeneously throughout the domain, imparting uncertainty into the results. However, the good agreement between inferred velocities based on embayment-wide mean thermocline movements and velocities measured at the ADCPs (Fig. 7) suggests that measured velocities were representative of basin-wide velocities. The relatively long excursion length scales suggest that significant exchange, with a minimal amount of short-circuiting, could have taken place during large-amplitude internal wave events. Additionally, the strong directionality of the currents on the north and south shores, leading to the counterclockwise residual circulation, furthered exchange with the main basin.

**Implications for aquatic life and water quality**

Isotherm movements mirrored those of the thermocline, resulting in spatially and temporally dynamic aquatic thermal environments. Coldwater fishes could be forced to respond to the large vertical isothermal oscillations we observed (Fig. 2d, Supporting Information Fig. S1) in an effort to remain in their preferred thermal habitat. A strong thermal and density gradient across the metalimnion impeded vertical mixing in the water column, limiting the flux of DO from the surface to depth (Chowdhury et al. 2015). This can exacerbate the formation of hypoxic conditions in the metalimnion and hypolimnion, as observed during the 2015 observation campaign, especially just below the thermocline (Fig. 2g). The seasonal depletion of DO within the metalimnion and hypolimnion could reduce the habitat volume available for coldwater species and degrade the aquatic ecosystem in general, impacting indicators used to evaluate lake health (Young and La Rose 2014). The fluctuating internal wave field could be one mechanism that regulates metalimnetic and hypolimnetic hypoxification by exchanging water with the main basin. The efficiency of this mechanism was controlled by internal wave energetics and structure, i.e., mode 1 or mode 2, and the amount of DO in the main basin hypolimnion, among others.

Sessile and low-motility organisms, such as phytoplankton, zooplankton, and even larval fish, are often carried by water currents (de Kerckhove et al. 2015), and their spatial and temporal distribution within Kempenfelt Bay could thus be a function of the residual circulation and flushing dynamics. This could in turn influence the feeding and foraging patterns of larger planktivorous and piscivorous species (de Kerckhove et al. 2015). The observed circulation patterns in Kempenfelt Bay could likewise influence the spread of current and future aquatic invasive species in Lake Simcoe as occurred with Asian clams in the deep, stratified Lake Tahoe (Hoyer et al. 2015).

Kempenfelt Bay receives significant nutrient and contaminant loads: both point source in the form of wastewater treatment plant effluent and tributary input, and nonpoint source via agricultural and road salt runoff, negatively affecting its water quality (Winter et al. 2007; LSPP 2009; North et al. 2013). An understanding of the dominant processes and associated time scales by which water quality constituents are transported out of Kempenfelt Bay is thus essential for informing lake management and policy, as well as for improving ecological modeling studies, such as those by Gudimov et al. (2012, 2015), by constraining the flushing rate estimates with realistic values derived from field observations and hydrodynamic models. We have provided evidence that exchange due to thermocline pumping can be an important mechanism for maintaining water quality in Kempenfelt Bay. The residual counterclockwise circulation highlighted by the gradients of SC (Fig. 9) would presumably also transport water quality constituents such as nutrients and contaminants introduced from Barrie and the surrounding catchment. As such, we might expect water quality gradients in Kempenfelt Bay to match SC gradients. Internal wave oscillations are likely to be similarly important in other embayments that are subject to energetic thermocline dynamics such as arctic fjords and the multitude of large, deep embayments in the Laurentian Great Lakes.

**Conclusion**

Free and forced internal waves energized by wind forcing and influenced by the Earth’s rotation are the dominant mechanism driving exchange of water in Kempenfelt Bay with the main basin of Lake Simcoe. We have demonstrated how vertical thermocline oscillations drive horizontal currents that pump water into and out of Kempenfelt Bay, resulting in epilimnetic (hypolimnetic) flushing times that could be as short as 17 ± 6 (13.5 ± 5) d during the summer-stratified period. As a result of rotational effects on the horizontal water currents, a persistent counterclockwise residual circulation leads to further exchange. Due to the good agreement between predicted (thermocline-derived) and measured (ADCP observations) width-averaged epilimnetic currents, we believe thermocline pumping, coupled with a secondary counterclockwise residual circulation, to be the main mechanism for exchange between Kempenfelt Bay and the main basin of Lake Simcoe. With large inputs of nutrients and contaminants coming from Barrie and the surrounding catchment, being able to accurately estimate exchange rates in Kempenfelt Bay is crucial for water quality and habitat protection efforts. Similar baroclinic processes are likely to occur in analogous systems, suggesting internal wave dynamics could be an important exchange mechanism in the multitude of long, deep embayments in the Laurentian Great Lakes and Arctic fjords. These findings could be used to support and improve ecological modeling efforts where system flushing times are often an important, but underinvestigated parameter.

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Conflict of Interest

None declared.

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