

Periodic boundary layer separation and lateral intrusions observed above a sloping lakebed

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Abstract

Lateral intrusions flowing from the boundaries of lakes and oceans might influence basin-scale distributions of heat, chemical solutes, sediments, and organisms. Here, observations of numerous intrusions from multiple locations in a small lake were used to examine the relation of intrusions to a lakewide internal seiche, and to estimate mean exchange between sloping bottom boundary layers (BBLs) and the lake interior. BBL waters were observed periodically separating from the bed and flowing laterally offshore. Boundary layer separation was initiated where strong downslope flows encountered upslope-propagating temperature fronts. These separation events propagated upslope, coherent with the vertically propagating internal seiche, resembling previously reported cases of upslope-propagating internal bores. Following separation, jets flowed offshore immediately above temperature fronts, transporting boundary layer water at least 61 m into the interior. Jet propagation could be traced upwards, from the bed at 9.4 m depth to the base of the surface mixed layer. Mean offshore transport was most intense within the metalimnion (4–7 m depth). Intruding intermediate-temperature thermocline water was likely supplied both by river inputs and by boundary mixing of cold and warm waters. These findings suggest that periodic jets, resulting from seiche-induced boundary layer separation, transported significant quantities of water from the boundary layer toward the stratified lake interior, with possible implications for distributions of sediments, solutes, and organisms.

In the interior region of lakes and oceans, vertical turbulent mixing is often inhibited by stable density stratification. However, mixing can be greatly intensified in the near-bed region called the bottom boundary layer (BBL) (Wuest and Lorke 2003; Trowbridge and Lentz 2018; Henderson and Nielson 2022). When lateral exchanges occur between boundary-mixed regions and the stratified interior (hereinafter BBL-interior exchanges), intense near-boundary mixing may influence basin-scale transport in both lakes (Goudsmit et al. 1997; Wuest et al. 2000) and oceans (Ledwell et al. 2000; McDougall and Ferrari 2017). BBL-interior exchanges are vital, partly because they transport heat, sediments (Ostrovsky and Yacobi 1999; Tian et al. 2019), and chemicals (Ostrovsky et al. 1996; McPhee-Shaw 2006) from boundary regions of intense mixing into the interior. Furthermore, as interior waters replace exported boundary-mixed waters, near-bed stratification may be replenished—a requirement for

continued efficient BBL mixing (Garrett 1990; Gloor et al. 2000). Despite the significance of BBL-interior exchanges, cases where exchange flows are traced in detail from the BBL to the interior have been limited to isolated events (e.g., Marti and Imberger 2008; Inall 2009; Wain et al. 2013). These observations demonstrate the potential importance of intrusions, but more spatially extensive observations are needed to map the distribution of intrusions throughout basins, and more temporally extensive observations are needed to evaluate the influence of intrusions on time-averaged transport.

Internal waves can generate sharp temperature fronts, which are sometimes associated with BBL-interior exchanges. For example, in lakes and the coastal ocean, internal waves generated by winds or tides can periodically transport dense waters upslope, with upslope-propagating fronts forming at the leading edge of the dense water masses (Thorpe and Lemmin 1999; Boegman et al. 2005; Cossu and Wells 2013). Sometimes, these fronts steepen near the bed to form breaking “internal bores” (Lamb 2014). When downslope-flowing lower-density BBL waters encounter fronts, the BBL waters can be lifted (“separated”) from the bed, and deflected to form intrusion currents or jets flowing offshore immediately above temperature fronts (Fig. 1, Cheriton et al. 2014; Masunaga et al. 2017; slightly different separations occurring in a lower layer beneath fronts were described by Boegman and

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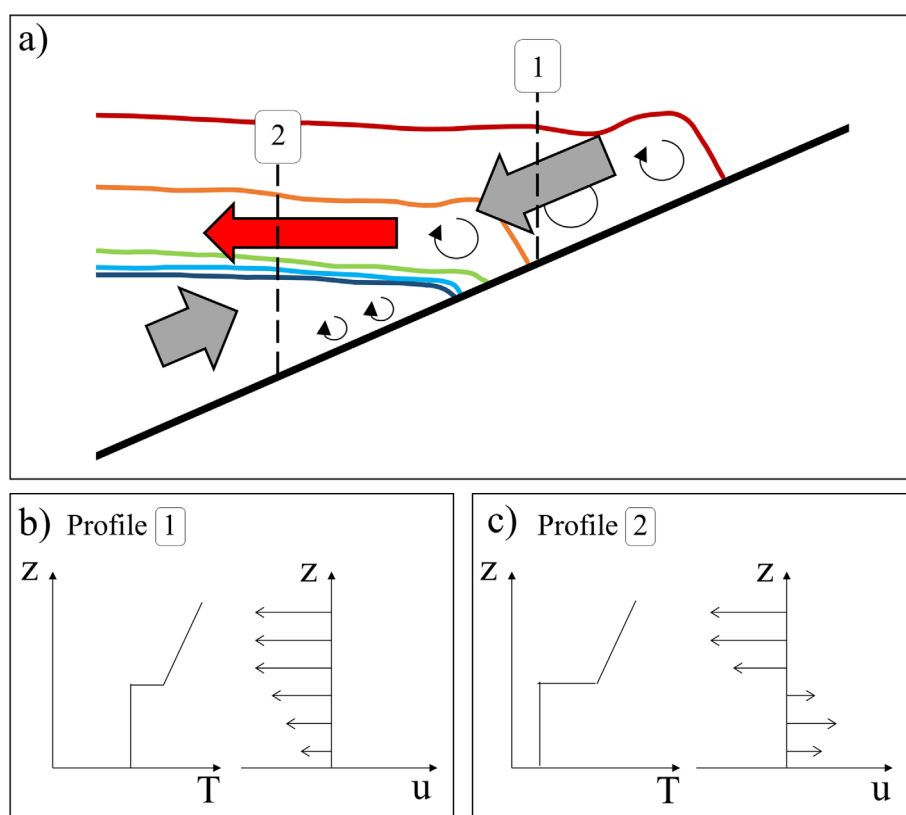


Fig. 1. Boundary layer separation and offshore flow. **(a)** A warmer mixed layer (bed-normal orange and maroon isotherms), associated with a down-slope current (upper gray arrow), converges with upslope-flowing colder waters (lower gray arrow) below a sharp temperature front (blue and green isotherms). The more buoyant layer is deflected offshore as a jet (red arrow) above the nearly horizontal front. Circular arrows indicate BBL mixing. Temperature and velocity along vertical profiles 1 and 2 (dashed lines, panel a) are illustrated in panels **(b)** and **(c)**. In temperature profiles, vertical lines indicate bottom mixed layers. As the front propagates upslope, temperature and velocity profiles at a fixed location may resemble profile 1 before front arrival, and profile 2 after front arrival.

Ivey 2009). Through multiple tidal cycles in the coastal ocean, periodic offshore jets can generate intrusions extending kilometers from slopes (Cheriton et al. 2014; Masunaga et al. 2017). In lakes, similar patterns of periodic boundary layer separation and lateral transport have been described, either near the stationary nodes of a vertically standing internal seiche (hereinafter “seiche”) (e.g., Boegman et al. 2003; Marti and Imberger 2008; Boegman 2009), or propagating up a slope with a vertically propagating seiche (Nielson and Henderson 2022). Vertically propagating seiches, which were examined previously using mid-lake observations (Henderson and Deemer 2012; Henderson 2016a), are contrasted with vertically standing seiches in Fig. 2. Previous studies have not compared detailed observations of small-scale flow separations (Fig. 1) with observations of larger, basin-scale seiching motions (Fig. 2).

In a small reservoir called Lacamas Lake (Camas, Washington), Nielson and Henderson (2022) showed that BBL separation occurred repeatedly, providing an opportunity for a detailed examination of intrusions. However, Nielson and Henderson (2022) focused on BBL turbulent mixing, leaving the contribution of

intrusions to offshore transport and their role in BBL-interior exchanges unexplored. Here, separation events measured during two successive years at multiple locations in Lacamas Lake were used to examine the relationship between BBL separation, the internal seiche, and lateral transport. High-resolution profiles of BBL temperature and velocity were used to describe the flows associated with BBL separation. Profiles spanning the metalimnion were used to describe vertical propagation of separated jets, and profiles from adjacent sites were used to trace jets a short distance from the BBL into the stratified interior. Transport was averaged over many seiche cycles to evaluate the contribution of jets to BBL-interior exchanges, and to estimate the rate at which exchanges could replenish interior waters. These results are compared with previous studies, and implications of periodic BBL separation are discussed.

Methods

Field site

Lacamas Lake is a small monomictic reservoir in the northwest United States. Narrow basin geometry (Fig. 3) constrains across-lake currents and limits the influence of Coriolis,

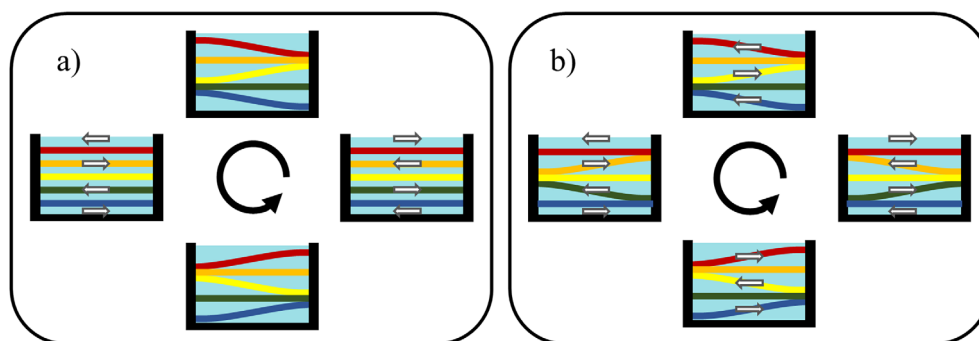


Fig. 2. Schematic showing idealized (a) vertically standing, and (b) vertically propagating, internal waves. In each panel, four successive cross-sections are drawn a quarter-cycle apart to illustrate a complete wave cycle. Colored curves indicate tilting of isotherms, and white arrows indicate water velocity. Panel (a) shows a vertical mode three, with three velocity reversals along each vertical profile, but vertical modes 1, 2, 3, 4, and higher, are also possible, depending on vertical wavelength. Seiches in many lakes resemble (a), with strong reflection from the bed (reflection coefficient $R \approx 1$). However, dissipation in the bottom boundary layer can lead to significant vertical propagation ($R < 1$). Panel (b) illustrates the vertically propagating seiche that would result from complete absorption ($R = 0$; the pictured upward phase propagation corresponds to downward energy propagation). Propagation, which is sometimes represented in simulations as coupling between standing modes (Brink and Allen 1978; Shimizu and Imberger 2009), was first identified in Lacamas Lake (Henderson and Deemer 2012; Henderson 2016b). Re-examination of previous observations indicates other cases of discernable net propagation [see fig. 8 of Serra et al. (2007); figs. 6, 8 of LaZerte (1980); and figs. 6, 8 of Vidal and Casamitjana (2008)].

yielding dominant along-lake flows (Henderson and Deemer 2012). Summertime tracer releases indicate that river inflow at the lake's northwest end plunges below the surface mixed layer, before intruding into the interior between about 4 and 7 m depth (Harrison 2021 pers. comm.). Surface water flows out at the southeast end. Beneath the surface mixed layer, currents are forced by vertically propagating wind-generated internal seiches with horizontal and vertical

wavelengths of approximately 3000 m (twice the lake length) and 6 m, and periods between about 0.5 and 1 d (Henderson and Deemer 2012).

Data were collected during 13 June to 25 August 2015, and during 7–21 September 2016. Observations were obtained from four sites in 2015 (S2 and S4–6, white circles, Fig. 3a) and two sites in 2016 (S1 and S3, black circles, Fig. 3a). Boundary layer separation was examined by comparing observations

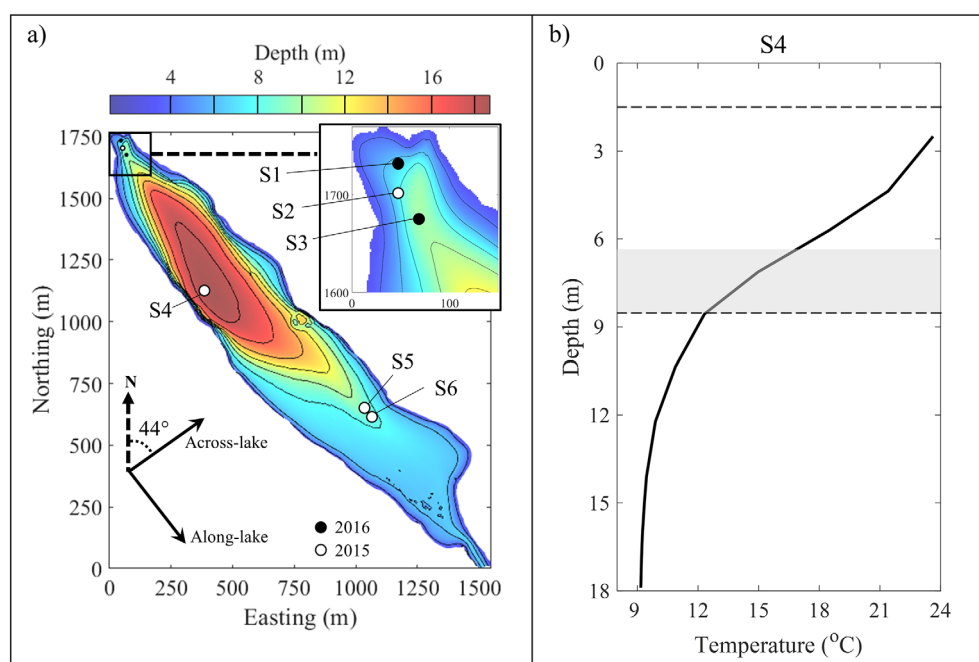


Fig. 3. Lacamas Lake, (a) showing depths and locations of study sites from 2015 (white circles) and 2016 (black circles). Origin of coordinate system at 45.6098°N, 122.4366°W. (b) Deployment-long average temperature profile from S4, with approximate coverage of velocity measurements at S6 (gray box) and S3 (dashed box).

obtained from closely-spaced pairs of sites. One pair, on the slope at the inlet end, was horizontally separated by 61 m (S1 and S3, depths 6.6 and 9.4 m). A second pair, on the slope at the outlet end, was separated by 32 m (S5 and S6, depths 8.4 and 8.2 m). At all sites, instruments were mounted on aluminum plates resting flat on the lakebed, and on an attached vertical line, which was held taut by a subsurface buoy. The deployment-long average profile from S4 shows strong summertime stratification (Fig. 3b), typical in Lacamas (Nielson and Henderson 2022), and the approximate coverage of velocity instruments from sites S6 and S3 (described below). The mean temperature gradient was particularly strong between 4 and 7 m depth, a region hereafter referred to as the metalimnion.

Instrumentation

Vertical lines of RBR Solo-T loggers measured temperature every 4 s with an estimated accuracy of $\pm 0.006^\circ\text{C}$. At all sites, 10–14 such loggers measured stratification with high spatial resolution within 2 m of the bed (Supplementary Table S1). At S1, S3, S4, and S6, additional loggers measured stratification with lower vertical resolution at higher elevations, spanning most of the water column. Each line of temperature loggers was equipped with an RBR Solo D pressure logger to determine instrument depths.

Paired upward-facing 2-MHz Nortek Aquadopp Acoustic Doppler Current Profilers (ADCPs) were deployed at S6 in 2015, and at S3 in 2016. Both ADCPs in 2015, and one ADCP in 2016, operated in pulse-coherent mode, measuring velocity with high spatial resolution (1.5-cm vertical bins, with two 0.5-s samples every 15 s) along profiles extending from $z = 0.155$ m to 2.06 m, where z is the elevation above the local bed (corresponding depths for S6 are indicated by a gray box in Fig. 3b; all elevations subject to a 1–4 cm error owing to frame settling and sedimentation during the deployment). During 2016, one ADCP operated without pulse-coherent sampling, providing longer profile range, extending to $z = 7.9$ m, at the cost of lower spatial resolution (0.75 m vertical bins; depth range indicated by dashed lines in Fig. 3b). For the pulse-coherent instruments, estimated root-mean-squared (rms) velocity errors were just under 1 mm s^{-1} for 0.5-s measurements, and comparisons between paired instruments indicate significantly smaller errors in half-hourly running means (Henderson 2016a, b). For the longer-range profiler, manufacturer's estimates suggest rms error of 2.4 mm s^{-1} in half-hourly averaged velocity. This estimate is consistent with an estimate obtained by Henderson (2016b) from the high-frequency noise floor in the velocity spectrum when bin size is accounted for (manufacturer's estimates are also supported by comparisons between biased and unbiased estimates of velocity variance, Henderson et al. 2017).

All instrument clocks were synchronized prior to deployment. Upon recovery, clock drifts of a few seconds were observed.

Data analysis

Water density was estimated using temperature and a fresh-water equation of state. Density (ρ) profiles were converted to buoyancy $b = g(\rho_0 - \rho)/\rho_0$, where $g = 9.80 \text{ m s}^{-2}$ and the reference density $\rho_0 = 1000 \text{ kg m}^{-3}$. The intensity of stratification was quantified by the squared buoyancy frequency $N^2 = db/dz$, where the vertical derivative was estimated using adjacent temperature measurements. A conservative minimum resolvable N^2 was estimated as 10^{-4} s^{-2} using a doubled temperature error (0.012°C) and the smallest vertical logger spacing (0.1 m; larger spacing gives smaller N^2 error).

Temperature fronts were identified as local maxima in N^2 , with peak values exceeding $5 \times 10^{-3} \text{ s}^{-2}$. Cases where such fronts could be traced propagating between the bed and $z > 1.5$ m coincided with prolonged boundary layer separation [see Nielson and Henderson (2022)]. At each end of Lacamas (sites S2 and S6), all such “BBL separation events” were identified and the time of frontal arrival at the lowest instrument location ($z = 0.17$ or 0.18 m) was recorded.

Vertical frontal propagation was compared with seiche propagation. Owing to BBL dissipation in the deep lake, the seiche in Lacamas propagates with an upward phase speed (c_z) near the theoretical speed of a linear, hydrostatic internal wave (Henderson and Deemer 2012):

$$c_z = \frac{2\pi\sigma^2\lambda_x}{\bar{N}} \quad (1)$$

where σ is the wave frequency, λ_x is the horizontal wavelength of the seiche (3000 m, twice the lake length), and $\bar{N}$ is the buoyancy frequency associated with the mean temperature profile. The associated time for propagation (t_p) between heights z_1 and z_2 is

$$\Delta t_p = \int_{z_1}^{z_2} \frac{dz}{c_z}. \quad (2)$$

Propagation times were calculated from Eqs. 1 and 2 and the temperature profile at S4, using a typical seiche period of 0.75 d. These seiche propagation times were compared with observed times for upward propagation of fronts.

Temperature measurements were also used to define a lakewide seiche phase. Temperatures measured at opposite ends of the lake (at $z = 1$ m at sites S2 and S6) were differenced to obtain a time series ΔT . To focus on seiche motions, rather than slowly-varying currents or higher-frequency waves and turbulence, ΔT was band-passed to remove oscillations with long (> 1.3 d) and short (< 0.4 d) periods. The seiche phase ϕ_H was then calculated as the complex argument of the Hilbert transform of band-passed ΔT (Bendat and Piersol 2000). The resulting time series of ϕ_H measured progress through seiche cycles, increasing by 360° each cycle, and enabled comparison with the timing of BBL separation. To compare BBL separation events measured at the bed with ϕ_H

measured 1 m above the bed, a time lag correction was applied using Eqs. 1 and 2.

The transport of separated BBL water toward the interior was evaluated at S3 using isothermal-mean analysis (McDougall and McIntosh 2001; Henderson 2016a). Water was partitioned into temperature classes, and a mean transport velocity u_T was calculated from the mean depth-integrated transport of water in each class. The velocity u_T associated with a specific temperature class is attributed to the mean depth of that class, and provides an estimate of the Lagrangian-mean velocity of water particles averaged over seiche periods, accounting for Stokes-drift corrections. Deployment-long average velocities are presented, but a 4-d running mean was used to separate seasonal and seiche-induced fluctuations (Henderson 2016a). To estimate near-surface transport, the velocity measured at the highest ADCP bin was extrapolated to the surface. Below the lowest ADCP bin, velocity was assumed to trend linearly to zero at the bed. Resulting errors in estimated near-bed transport are likely small, given small near-bed velocities. In contrast, errors in near-surface transport may be substantial, because near-surface velocity and neglected shear can be large, and because the highest ADCP bin was 1.8 m from the surface at S3. To examine the role of jet-like intrusions, jets were identified as regions of strong offshore velocity ($>0.02 \text{ m s}^{-1}$) immediately overlying fronts (at S3, these regions ranged in thickness from 0.75 m near the bed to 1.5–2.25 m higher in the water column). Mean transport velocities were calculated twice, once including jet velocities, and once with jet velocities set to zero. The difference between the two estimates was the transport velocity resulting from jets.

To approximately evaluate the potential of the observed mean transport velocity to flush the stratified interior, the water column was divided into shallow (0–4 m depth) and metalimnion (4–7 m) layers. The “interior” was identified as the region between the along-lake coordinates of S3 and S6. From measured bathymetry, a trapezoidal interior volume V was estimated between S3 and S6 as 1.75×10^6 and $1.07 \times 10^6 \text{ m}^3$, respectively, for shallow and metalimnion layers. At S3, the areas A_v of vertical, across-lake cross-sections were estimated as 420 and 207 m^2 for the two layers. For each layer at S3, the lateral flux of boundary waters into the interior, in $\text{m}^3 \text{ s}^{-1}$, was estimated as $Q = A_v \bar{u}_T$, where $\bar{u}_T$ was the layer-average of u_T . At S6, similar calculation was not possible using the measurements presented here, because only short-range ADCPs were deployed at that site. Instead, fluxes were estimated from u_T measured very near S6 during the same season in 2012 (Henderson 2016a; upper and lower areas A_v at S6 were 1352 and 732 m^2). The lateral fluxes from the two lake ends were found to converge in the metalimnion, adding water to the lake interior, and to diverge in the surface layer. For each layer, a residence time was calculated as $V/|\Delta Q|$, where ΔQ is the total lateral flux into the interior from both lake ends. An associated mean upward velocity between lower

and upper layers was estimated as $|\Delta Q|/A_h$, where A_h is the lake’s horizontal area between S3 and S6 at 4-m depth.

Backscatter intensities measured by ADCPs often provide qualitative information about sediment concentrations in the water column, although backscatter can also be affected by plankton and small-scale temperature variability (Lavery et al. 2013). Raw backscatter amplitudes (A), in counts, were corrected for sound attenuation and converted to decibels (BS_{dB}) using

$$BS_{dB} = As + 20 \log_{10}(R\psi) + 2\alpha_w R, \quad (3)$$

where $s = 0.43$ counts/dB, R is the along-beam range, ψ is a near-field correction (eq. 18 of Downing et al. 1995), and the water absorption coefficient $\alpha_w = 1.19$ was estimated from fig. 1 of Lohrmann (2001). Eq. 3 was applied to each of the three ADCP beams, and reported BS_{dB} values are averages across the three beams.

Results

Temperature oscillations and internal seicheing

Owing to the lakewide seiche, temperatures measured near the base of the metalimnion (7 m depth) oscillated with approximately a 0.5- to 1-d period (Fig. 4a). Consistent with the horizontal mode-one seiche structure (Henderson and Deemer 2012), temperature oscillations at opposite ends of the lake (sites S2 and S6) were about half a cycle out of phase. As defined, seiche phase $\phi_H \approx 180^\circ$ when temperature was maximum at S2 (e.g., vertical dotted line, Fig. 4a,b) whereas $\phi_H \approx 0^\circ$ or 360° when temperature was maximum at S6 (e.g., vertical dashed line).

Detailed observations of boundary layer separation

A typical BBL separation event at S6 is shown in Fig. 5. During the period shown, near-bed temperature steadily increased until the sudden arrival of a cold-water layer on yearday 198.99 (Fig. 5a). The cold layer was capped by an intense temperature front, which yielded a thin interface of high N^2 (Fig. 5b, dashed line). This cold front extended almost horizontally to nearby site S5 (not shown). A similar, but less intense, interface of high N^2 capped a warmer bottom mixed layer prior to front arrival (Fig. 5b, solid line).

Downslope velocities ($u < 0$, blue in Fig. 5c) were associated with increasing temperatures (Fig. 5a), as warmer water was advected from higher elevations (consistent with profile 1 of Fig. 1b). At front arrival, the downslope-flowing buoyant water was lifted from the bed, above the upslope-flowing cold layer. Vertical velocities in this buoyant layer, integrated for 5 min during separation, matched the layer’s vertical displacement (not shown). Following separation, relatively high velocities persisted within the buoyant layer, forming a detached jet of offshore-flowing water immediately above the cold front (consistent with profile 2 of Fig. 1c). After yearday 199.05, the

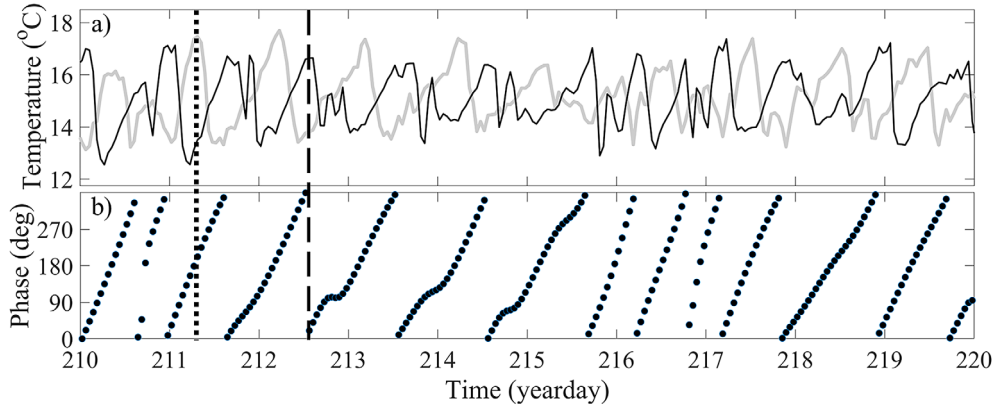


Fig. 4. Time series of temperature fluctuations and seiche phase. **(a)** Hourly-mean temperatures measured 1 m above the bed near the inlet (S2, gray line) and outlet (S6, black line). **(b)** Seiche phase as characterized by band-passed difference between temperatures shown in **(a)**. Dashed line marks a local maximum temperature at S6, which corresponds to a phase near 0° or 360° . Dotted line marks a local maximum at S2, which corresponds to a phase near 180° .

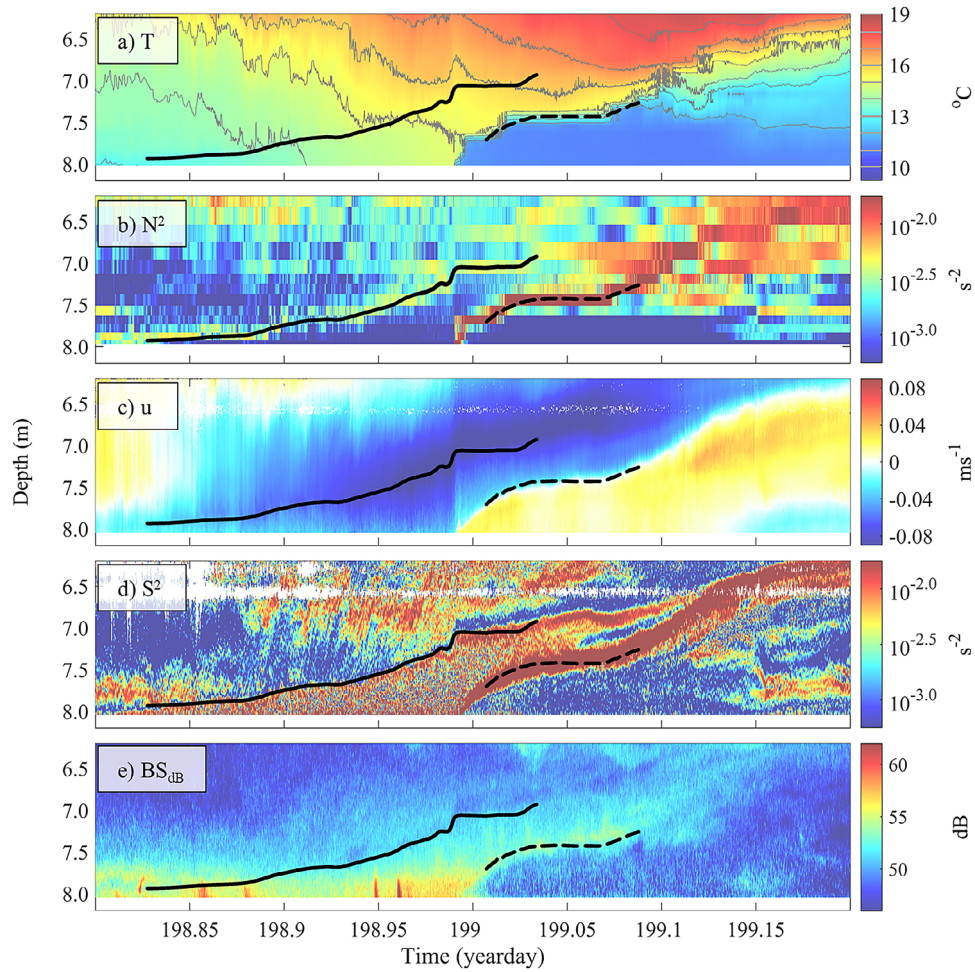


Fig. 5. Observations at S6 showing boundary layer separation at yearday 198.99. All vertical axes extend to the bed at 8.2 m depth. Intensified stratification marking the top of warm and cold mixed layers respectively marked by solid and dashed black lines. **(a)** Temperature, **(b)** squared buoyancy frequency N^2 , **(c)** velocity (positive upslope), **(d)** squared shear S^2 , **(e)** relative backscatter.

upper part of the jet moves above the 2-m profile shown in Fig. 5. The separation of the boundary layer was particularly clear in squared shear S^2 (i.e., the squared vertical derivative of the velocity, Fig. 5d). Prior to front arrival, shear was elevated in the buoyant bottom mixed layer below the high- N^2 cap (i.e., below the solid line). This high-shear layer was displaced above the intense cold front (dashed line) during flow separation. A band of particularly intense shear coincided with the cold front (dashed line).

Prior to front arrival, backscatter was elevated within the warm bottom mixed layer (beneath the solid line, Fig. 5e). Following BBL separation, backscatter within the separated layer remained elevated, whereas near-bed values below the cold front (dashed line) were low.

Timing of BBL separation

All temperature fronts that propagated between the bed and $z = 1.5$ m, here called “separation events,” resembled the flow separation shown in Fig. 5. Specifically, such fronts all propagated upwards (i.e., no cases of downward frontal propagation from $z = 1.5$ m to the bed were observed), and transitions from downslope to upslope flow always coincided with frontal arrival at the bed. During 2015, the Hilbert transform indicated 94 seiche cycles, while a total of 75 and 92 separation events were identified at S2 and S6, respectively. Therefore, separation occurred during most seiche cycles. When plotted by seiche phase, separation events clustered around $\phi_H = 180^\circ$ for S2 and $\phi_H = 0^\circ$ for S6 (Fig. 6). Therefore, separations were coherent with the lakewide seiche, alternating between inlet and outlet ends. Since arrival of temperature fronts coincided with velocity reversals at the bed, similar results are obtained if velocity reversals are used to identify separations (not shown).

Vertical extent of BBL separation

Observations near the inlet (S3) highlight the vertical extent and propagation of BBL separation events. Temperatures oscillated with 0.5- to 1-d period owing to the seiche (Fig. 7a), and temperature fronts were observed propagating upward (black lines, Fig. 7b). As was observed near the outlet, frontal arrivals at the bed (9.4 m depth) coincided with transitions from downslope to upslope flow (yellow to blue, Fig. 7c). Note that downslope or offshore velocities are positive near the inlet (Fig. 7), but negative near the outlet (Fig. 5). Jets continued to flow offshore immediately above fronts (bands of red immediately above black lines, Fig. 7c) even as the fronts propagated well above the bed. These offshore jets eventually reached the base of the mixed layer (about 4 m depth), with particularly strong flows between about 4 and 7 m depth. Immediately below fronts, water flowed more slowly onshore.

Fronts propagated upward across the elevations of individual isotherms (Fig. 7a,b), indicating that water was not advected upward with the fronts. Therefore, frontal propagation could not be explained by oscillating advection of a

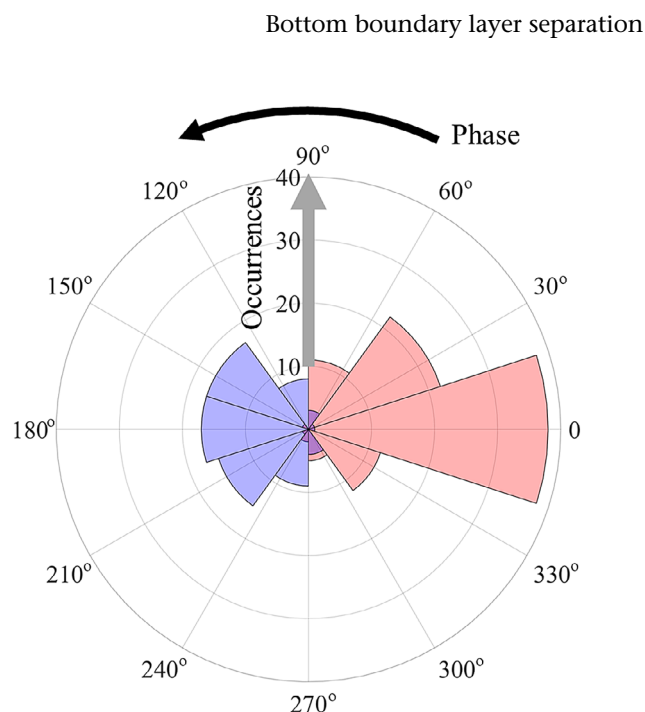


Fig. 6. Polar histogram showing the seiche phase ϕ_H associated with BBL separation events. Values around the perimeter (black arrow) indicate phase in degrees. Each wedge represents a 36° range of seiche phase, and the radial length of each wedge indicates the number of occurrences (gray arrow) of separation events observed in the given phase range. Blue and red wedges respectively indicate separation events observed near the inlet (S2) and outlet (S6).

consistently sharp thermocline. Instead, fronts were likely generated by the strain field associated with the upward-propagating internal seiche. At S3, over days 257–265, the observed time for vertical propagation of fronts from 9.4 to 6.6 m depth was between 4.1 and 10.5 h, with an average of 7.2 h, comparable to the vertical seiche propagation time of 7.3 h (Eqs. 1 and 2). Therefore, the consistent phase between fronts and the lakewide seiche (Fig. 6) was likely maintained as the seiche propagated up through the lake.

Lateral extent of BBL separation

To evaluate the lateral extent of BBL separation, observations from S3 (Fig. 7) were compared with observations obtained 61 m onshore at S1 (Fig. 8). Frontal elevations determined from temperatures at S3 (dashed lines, Fig. 8) coincided with fronts at S1 (yellow or red bands, Fig. 8). Close examination shows that temperatures also coincided. Therefore, fronts and associated isotherms extended horizontally over at least the 61 m between S1 and S3. Furthermore, velocities of about 0.03 m s^{-1} in offshore jets (Fig. 7c) suggest a between-site advection time of about 30 min. Since the elevated velocities persisted for several hours, there was ample time for the water that separated from the bed at S1 to flow past S3.

In the metalimnion of Lacamas, the turbulent BBL often extends 0.5–1 m vertically above the lakebed, which corresponds to a horizontal extent of 11–22 m given the observed

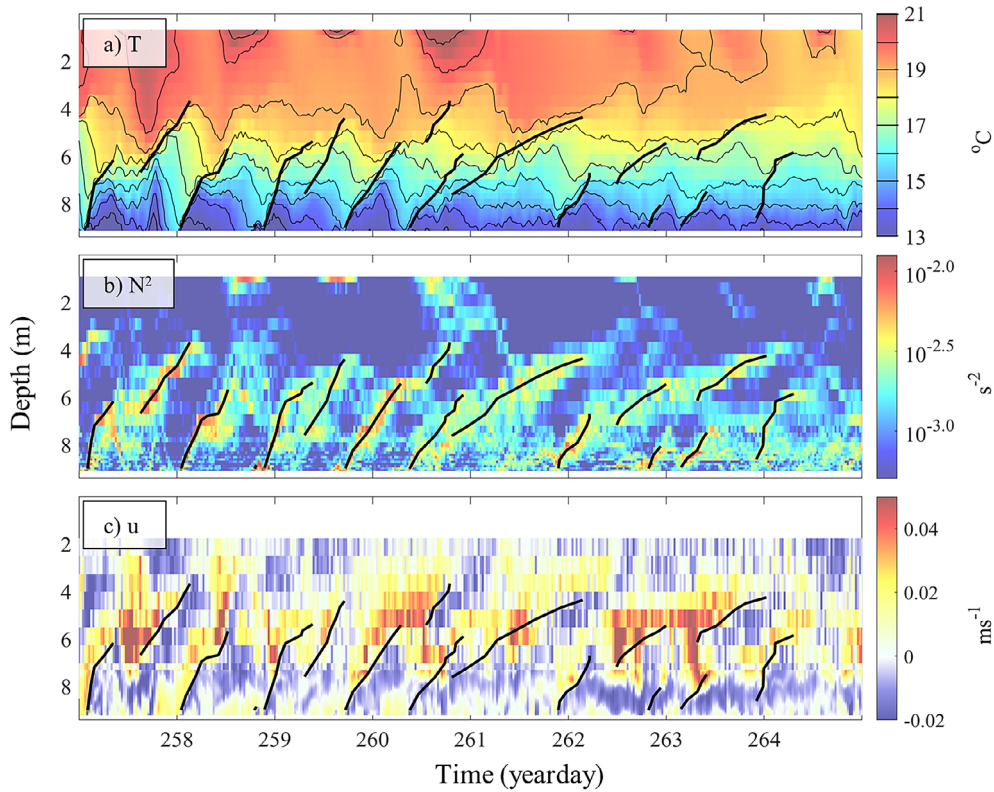


Fig. 7. Time series observations of (a) temperature, (b) squared buoyancy frequency, and (c) velocity at S3. All vertical axes extend to the bed at 9.4 m depth. Temperature fronts (black lines), and overlying offshore jets (positive velocities at the inlet end), repeatedly propagated from the bed to the base of the surface mixed layer.

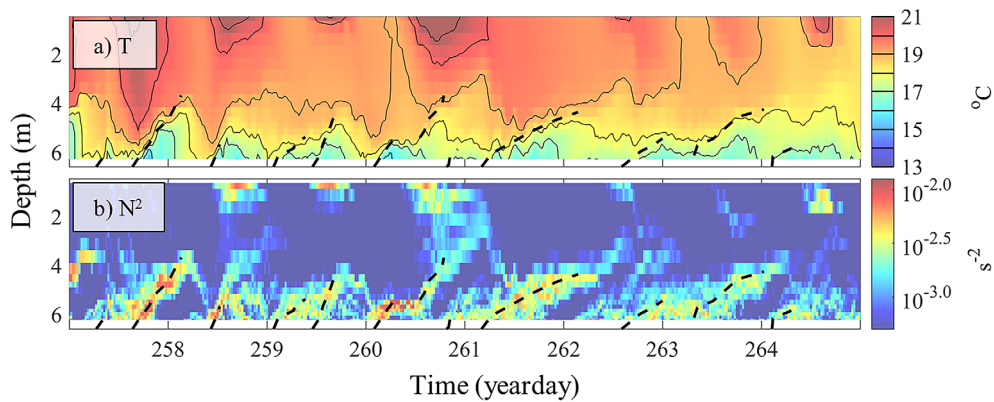


Fig. 8. Time series observations of (a) temperature and (b) squared buoyancy frequency from S1. Vertical axes extend to the bed at 6.6 m depth. Dashed lines mark fronts at S3, 61 m offshore of S1 (same as black lines in Fig. 7).

bed slope between S1 and S3. Therefore, the observed jets transported water well outside the BBL. It is unclear how far the jets traveled beyond S3 into the stratified interior.

Mean transport

At S3, mean transport was mostly offshore (i.e., toward the lake interior, Fig. 9, black curve), except for thin regions near the bed (> 7.5 m) and near the surface (< 2.5 m). Averaged

across shallow (0–4 m depth) and metalimnion (4–7 m) layers, transport velocities at S3 were 0.1 and 9.3 mm s^{-1} . Corresponding velocities near S6 during the same season in 2012 were 8 mm s^{-1} onshore and 3 mm s^{-1} offshore in shallow and metalimnion layers [fig. 10 of Henderson (2016a)]. When the contribution of offshore jets was removed (Fig. 9, gray curve), mean metalimnion transport at S3 was reduced by 72%. Therefore, in the metalimnion, jets were responsible

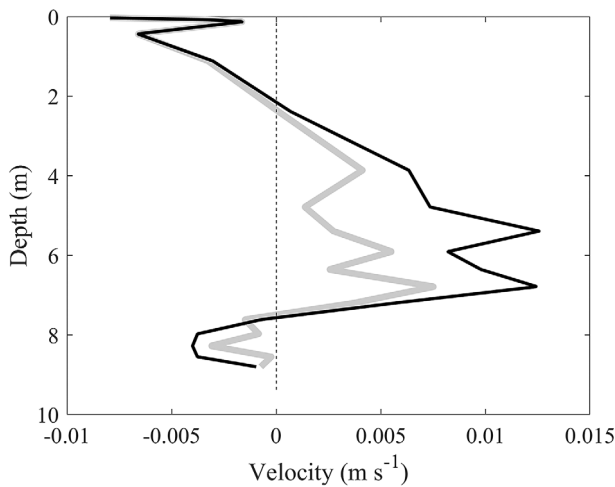


Fig. 9. Profile of mean transport velocity u_T , with (black) and without (gray) the contribution of offshore-flowing jets.

for most transport of water away from the sloping bed toward the stratified interior.

At S3, estimated offshore mean flux Q was $-0.04 \text{ m}^3 \text{ s}^{-1}$ in the shallow layer and $1.9 \text{ m}^3 \text{ s}^{-1}$ in the metalimnion. Corresponding estimated fluxes toward the interior at S6 were -10.8 and $2.2 \text{ m}^3 \text{ s}^{-1}$. These outlet-end (S6) fluxes were substantial, despite small outlet-end velocities, owing to the relatively large outlet-end lake width. Extrapolation of the measured profile of weak mean velocity across such a wide lake width makes estimated outlet-end fluxes particularly prone to error. Transport from the lake ends converged in the lower layer and diverged in the upper layer. From this, lake-interior residence times of 1.9 and 3.0 d were estimated for the lower and upper layers, and a mean interior upwelling velocity at 4 m depth was estimated as $1.0 \times 10^{-5} \text{ m s}^{-1}$.

Discussion

Observed spatial and temporal structure of intrusion events

Through many cycles of an internal seiche, BBL waters were observed repeatedly separating from the bed and flowing laterally toward the lake interior. Strong temperature fronts propagated up the sloping lakebed. Upslope and downslope BBL flows converged on these fronts, and the downslope flows were deflected to create offshore-flowing jets immediately above the fronts (Figs. 1, 5). For any given depth in the metalimnion, one separation event was observed at each end of the lake almost every seiche cycle. Separations were coherent with the lakewide seiche, coinciding with the transitions from downslope to upslope flow (Fig. 6). Separated jets carried boundary layer water at least 61 m into the interior, and their vertical propagation could be traced from the bed at 9.4 m depth to the base of the surface mixed layer at about 4 m depth (Figs. 7, 8). This vertical propagation of separated jets was consistent with vertical propagation of the seiche, observed in this lake by previous researchers (Henderson and Deemer 2012; Henderson 2016b).

Figure 10 depicts the likely oscillating flow pattern in Lacamas. Consistent with previous observations, a lowest-horizontal-mode seiche is shown propagating vertically, with a vertical wavelength that increases with increasing depth, such that the total lake depth spans more than one complete vertical wavelength (Henderson and Deemer 2012). Consistent with the observations presented here, temperature fronts and separated jets are shown propagating up the sloping bed, with one flow separation from each end of the lake every seiche cycle.

The lakewide pattern of isotherm tilting shown in Fig. 10 could be anticipated from Fig. 2b. However, the intensity of the observed fronts, with temperature jumping several degrees within the 0.15 m sensor spacing (Fig. 5b), was not clear from

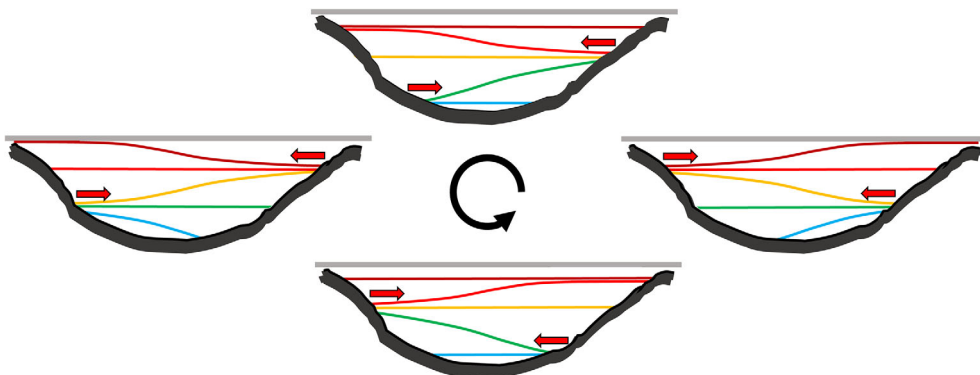


Fig. 10. Schematic showing vertical seiche propagation and BBL separation. The four successive lake cross-sections are drawn a quarter-cycle apart to illustrate a complete seiche cycle. Temperature fronts form at the lake ends where isotherms (colored curves) group together. Jets of separated boundary layer waters (red arrows) flow offshore immediately above these fronts. The patterns of fronts and separated jets propagate up the sloping bed at each end of the lake.

the previous mid-lake observations (Henderson and Deemer 2012; Henderson 2016a) on which Fig. 2b was based. Such intense fronts suggest local violations of the linear wave theory previously used to interpret observations of the lakewide seiche. Furthermore, the location of offshore jets immediately above temperature fronts could not be anticipated from linear theory. The observed formation of intense fronts with small isotherm slopes is consistent with the analysis of Thorpe (1992), which showed that nonlinear wave dynamics can lead to near-bed fronts, despite small isotherm slopes, if isotherm slope is comparable to bed slope. Consistent with observations, this theory predicts fronts that propagate with internal waves, crossing isotherms as they do so.

In the ocean, similar offshore jets have been observed above fronts formed by upslope-propagating internal tidal bores (Cheriton et al. 2014; Masunaga et al. 2017). In Lacamas, fronts did not exhibit the order-one frontal slopes associated with breaking bores, except possibly within 18 cm of the bed, where no measurements of temperature were made (Nielson and Henderson 2022). Therefore, steepening of fronts may not be essential to flow separation. In other lakes, separated jets have been observed near the thermocline (Ostrovsky and Yacobi 1999; Boegman et al. 2003; Marti and Imberger 2008). However, these jets were associated with intrusions near the base of the surface mixed layer or at the fixed nodes of vertically standing seiches. In contrast, the lateral jets in Lacamas propagated upslope with internal waves, like the cases observed in the coastal ocean (e.g., Masunaga et al. 2017). The conditions required for vertical seiche propagation are discussed by Henderson and Deemer (2012) and Henderson (2016b).

Note that the observed sudden transitions from down- to up-slope near-bed flow are a general property of upslope-propagating flow separations. Specifically, if a velocity field propagates upslope without changing form at speed c_{slope} , then $\partial u / \partial x = -(\partial u / \partial t) / c_{\text{slope}}$. Consequently, sudden transition to upslope flow (large $\partial u / \partial t > 0$) must be associated with intense convergence of bed-parallel flow (large $\partial u / \partial x < 0$), and therefore divergence of BBL waters from the bed.

The regular occurrence of separation events suggests regular renewal of BBL waters by exchange with the stratified interior. Some of the water carried away from the bed by offshore jets may cycle back into the BBL. However, the strength of the observed jets, and their extension far from the BBL region of intensified mixing, suggests that significant renewal of BBL waters each seiche period is possible, consistent with the simulations of Ulloa et al. (2019).

Potential formation of intermediate nepheloid layers

Separated jets can transport sediments and organic matter away from sloping beds (McPhee-Shaw 2006; Masunaga et al. 2017; Tian et al. 2019), forming thin layers of high sediment concentration called “intermediate nepheloid layers” (INLs). INLs may transport significant sediment volumes

toward lake interiors (Ostrovsky and Yacobi 1999; Samolyubov and Ivanova 2015). In Lacamas, high ADCP backscatter was observed within jets (Fig. 5e). Since such high backscatter can indicate high concentrations of suspended sediments or plankton (Hay 1983; Lavery et al. 2010), the separated jets in Lacamas may have contributed to sediment transport. However, ADCP backscatter can also be intensified by small-scale density fluctuations associated with turbulent mixing (Lavery et al. 2013). Consequently, without direct measurements of sediment concentration, the possible importance of separated jets to sediment transport in Lacamas remains uncertain.

Comparison with other intrusion mechanisms

Although the intrusions in Lacamas resembled those observed by Masunaga et al. (2017), they differ from several other forms of intrusion described by previous researchers. Intrusions may occur when bursts of intense turbulence generate well-mixed regions within the BBL, which subsequently slump toward the interior under the action of gravity (McPhee-Shaw 2006; Wain and Rehmann 2010). In Lacamas, separation was preceded by particularly intense BBL mixing (Nielson and Henderson 2022). However, the separated jets were not consistently more well-mixed (i.e., lower N^2), than the onshore-flowing water immediately beneath the fronts (Figs. 5, 7). This is likely because the intrusions were a coherent part of the internal wave velocity field, and were not generated solely by gravitational collapse of an isolated mixed region.

Laboratory experiments have shown that internal waves can generate nonpropagating intrusions with a vertical spacing much less than the internal-wave wavelength (McPhee-Shaw and Kunze 2002), possibly owing to various instability mechanisms (Thorpe 1998). In contrast, the intrusions in Lacamas propagated vertically, with a vertical spacing comparable to the vertical wavelength of the seiche (this spacing is implied by the equivalence of frequencies and propagation speeds). Intrusions can also be generated by changes in bed slope (Inall 2009), but such intrusions do not propagate upslope.

Intrusions can also result from mixing in the presence of depth-varying stratification. For example, where a stationary thermocline intersects a sloping boundary, BBL mixing of cold and warm waters generates water of intermediate density. By volume conservation, intermediate waters must then flow away from the BBL, with persistent mixing implying a persistent thermocline intrusion velocity (Phillips et al. 1986). In contrast to such a steady intrusion at a fixed thermocline, intrusions in Lacamas occurred as intense pulses associated with the passage of propagating fronts. Nevertheless, when averaged over many seiche periods, creation of intermediate waters by mixing may be rapid where the mean thermocline meets the sloping bed. Volume conservation then implies a mean transport of thermocline waters into the interior (Masunaga et al. 2017). Time-averaged transport in Lacamas

was consistent with this suggestion, as will be discussed in the next section.

Mean transport from boundaries

When averaged over many seiche periods, intrusions generated substantial mean offshore transport at metalimnion depths (4–7 m). The intermediate-density waters required to sustain this mean transport might be supplied by mixing, as outlined above, or by river inflows. Mean transport from the inlet end at metalimnion depths ($1.9 \text{ m}^3 \text{ s}^{-1}$) was comparable to typical summertime river discharge ($1.93 \text{ m}^3 \text{ s}^{-1}$, Deemer and Harrison 2019), suggesting a significant role for river inflows. However, separated jets were also observed near the outlet (S6). These outlet jets could not be explained by river inflows, suggesting a role for mixing. The associated mean transport velocity near the outlet was slow, but if maintained across the relatively large outlet-end lake width, this transport would contribute significantly to the total flux of thermocline waters into the lake interior.

Net lateral inflow at metalimnion depths and outflow in the surface layer suggests upwelling somewhere within the lake interior (Fig. 11). Estimated fluxes suggest residence times of 2–3 d for both the metalimnion and surface layers. These estimates are very approximate, because (1) across-lake variability was neglected when estimating fluxes, (2) it is not known how far the intrusions extend into the interior, and (3) different regions within the interior may be flushed at different rates. Also, extrapolation of ADCP measurements to the surface, which neglects near-surface velocity shear, makes surface-layer fluxes are particularly prone to error. Nevertheless, metalimnion flux estimates do not require such extrapolation, and the estimated inlet-end metalimnion flux agreed well with typical summertime river discharge.

Analysis based on previously published observations supports the interior upwelling, and order-of-magnitude residence times, estimated here. Specifically, upwelling must often occur

when riverine inflows intrude at the metalimnion and outflows are drawn from the surface layer (Killworth and Carmack 1979). Such cases are common in temperate lakes during summer (Peeters and Kipfer 2009). Dividing interior volumes of metalimnion and surface layers by river inflow ($1.93 \text{ m}^3 \text{ s}^{-1}$) then yields residence times of 6 and 10 d, respectively, for the two layers. Therefore, residence times within a factor of 2–3 of those estimated from our observations could be anticipated from using relatively well constrained estimates of river discharge and lake bathymetry. More novel than such calculations based on intrusions near the inlet is the additional flux resulting from intrusions near the outlet. The factor-of-two reduction in residence times associated with such outlet intrusions is highly uncertain. Nevertheless, these results show that near-boundary creation of mixed waters could potentially contribute significantly to lakewide circulation.

This study has examined exchanges between the boundary and the stratified interior, and does not consider spatial variability of flows and mixing within the interior. However, owing to such variability, some water particles may remain within the stratified interior longer than the calculated residence times if other particles move through the interior more quickly. More detailed observations or modeling studies would be required to examine this possibility.

Conclusions

As noted by previous researchers, seiche-coherent BBL separation may be a mechanism for BBL-interior exchanges, with potential implications for the transport of sediments, chemical solutes, and organisms. Here, temperature and velocity profiles observed in a small lake were used to examine separation and associated boundary-interior exchange. During two field campaigns, hundreds of BBL separation events were observed. Sharp horizontal temperature fronts formed where downslope-flowing BBL waters encountered upslope-propagating cold-water layers. Convergence of boundary-parallel flows initiated separation of the downflowing BBL waters, which detached from the bed and flowed offshore above the temperature fronts. Repeated separation events were coherent with the lakewide internal seiche. At a given elevation, separation events at each end of Lacamas occurred roughly once per seiche cycle. Upward propagation of temperature fronts and associated separated jets matched the upward propagation speed of the internal seiche. Jets were observed flowing at least 61 m into the stratified lake interior, although actual advection distances may have been greater. When averaged over multiple seiche cycles, the separated jets were responsible for a mean lateral flux from the sloping bed into the interior at metalimnion depths. Near the inlet, much of this flux may have been supplied by inflowing river waters. Near the outlet, the mean offshore transport at metalimnion depths may be explained if intermediate waters were created by BBL mixing of cold and warm waters.

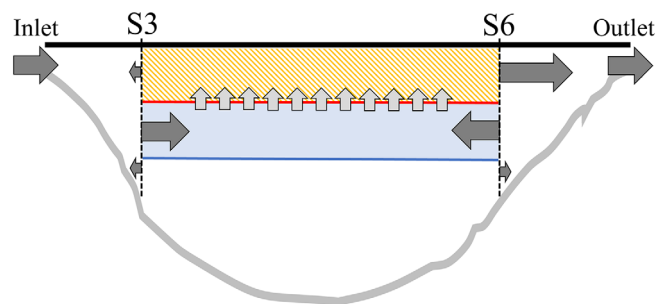


Fig. 11. Inferred mean advection in Lacamas. Black, red, and blue lines respectively indicate water surface, isotherm at 4 m depth, and isotherm at 7 m depth. Vertical dashed lines mark inlet and outlet sites of transport velocity profile estimates. Dark gray arrows represent estimated mean fluxes. Light gray arrows indicate interior upwelling, inferred from observed lateral convergence in the metalimnion (blue area) and lateral divergence near the surface (orange area).

Data availability statement

Data available by request.

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Conflict of Interest

None declared.

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