Interactive discussion on "Seasonality of density currents induced by differential cooling"

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Response to Referee #3

R (Referee):

In this manuscript, the authors use a unique year long time series to estimate the frequency and strength of the thermal siphon in lakes and the influence on flushing of the littoral zone. This is an interesting dataset and addresses an important concept in physical limnology. The writing and presentation are mostly very good.

A (Authors): We thank Referee #3 for his/her encouragement and his/her interesting questions about the interpretation of the results. We address all the comments from Referee #3 below.

I have a few general comments that I would like to see addressed though:

RC1 (Referee's Comment #1): *What is the magnitude of the outflow near the study site? Is it important relative to magnitude of the flushing rates?*

AR1 (Authors Response #1): There is no in-situ measurement in the outflow but the discharge can be estimated from the simulations of the Swiss river network (dataset MQ-GWN-CH from the Federal Office for the Environment). The monthly averaged simulated discharges of the Rotsee outflow in m^3 s^{-1} are available here:

https://api.geo.admin.ch/rest/services/ech/MapServer/ch.bafu.mittlere-abfluesse/67200/extendedHtmlPopup?lang=en.

The average discharge is ~ 0.1 m^3 s^{-1}, which corresponds to a specific-width discharge at MT (total width of 150 m) of $q_{out} \sim 7 \times 10^{-4}$ m^2 s^{-1}. This estimate is more than one order of magnitude smaller than the TS discharge $q_{avg} \sim 10^{-2}$ m^2 s^{-1} (Fig. 6). The effects of the outflow on the TS dynamics are thus negligible. We propose to mention the low discharge of the inflow and outflow on lines 108-109 as follows: *"The main in- and outflows are located at the south-western and north-eastern ends of the lake, respectively, and have a low discharge of ~ 0.1 m^3 s^{-1}."*

RC2: *What influence does the three-dimensionality of the littoral zone play? From my understanding, the entire framework here is 2D, but how uniform do you suppose q is across the lake? What are the limits of your results for other lakes in that context? It appears that Rotsee is about 2D as it gets, but is there a littoral zone aspect ratio where this all falls apart?*

AR2: The reviewer is correct: we used a 2D framework in this study and we focused on the lateral transport along the x-axis, as our objective was to quantify the flushing of the littoral plateau region at the north-eastern end of the lake. The elongated shape of Rotsee is suitable for this 2D framework, which is similar to the nearly 2D sidearm circulation observed in reservoirs (Adams and Wells, 1984; Monismith et al., 1990). We decided to take our measurements along the lake thalweg, which is the preferential direction of TS according to 3D numerical simulations (Ramón et al., 2019). We expect q to be lower if it is measured away from the thalweg, closer to the north-eastern or south-western shores. The validity of such a 2D framework has to be further evaluated in more complex nearshore systems that might deviate from the conceptual model adopted here. Coriolis effect and local bathymetry perturbations might have to be included in these cases. For instance, the downslope flows observed by Fer et al. (2002) in Lake Geneva are not perpendicular to the shore due to spatial irregularities of the littoral region. The 3D aspects of TS are out of the scope of this study, but could be a motivation for future work. In particular, the effect of the littoral zone aspect ratio on the TS dynamics could be investigated with 3D numerical simulations.

We will add a paragraph after line 113 to explain our 2D framework. We refer to the answer AR3 to Referee #2 for more details about this paragraph. We also propose to add a few sentences about the 3D effects in other lakes after line 573: *"Finally, the 2D framework of TS requires specific validation in more complex nearshore systems and large lakes, where the topography, large-scale circulation and Coriolis may also affect the TS dynamics (Fer et al., 2002b). In these systems, the along-shore velocity component of TS must be considered in the cross-shore transport analysis."*

References:

Adams, E. E. and Wells, S. A.: Field measurements on side arms of Lake Anna, Va., J. Hydraul. Eng., 110, 773–793, https://doi.org/10.1061/(ASCE)0733-9429(1984)110:6(773), 1984.

Fer, I., Lemmin, U., and Thorpe, S. A.: Winter cascading of cold water in Lake Geneva, J. Geophys. Res., 107, 3060, https://doi.org/10.1029/2001JC000828, 2002.

Monismith, S. G., Imberger, J., and Morison, M. L.: Convective motions in the sidearm of a small reservoir, Limnol. Oceanogr., 35, 1676–1702, https://doi.org/10.4319/lo.1990.35.8.1676, 1990.

Ramón, C., Doda, T., Ulloa, H., and Bouffard, D.: Density currents induced by night-time cooling: offshore transport of littoral waters, in: Geophysical Research Abstracts, Vienna, Austria, 7-12 April 2019, EGU2019-970, 2019.

RC3: *Given the time of year where TS is most prevalent, does this play a role in accelerating autumn turnover?*

AR3: This is an interesting point. Yet, the effects on autumn turnover are out of the scope of our study and we will not discuss them in the manuscript. The intrusion of TS at the base of the mixed layer modifies the vertical thermal structure by bringing cold water above the thermocline. This advective heat flux enhances the cooling of the surface layer and should accelerate the deepening of the mixed layer in autumn, as observed for differential heating under ice (Ulloa et al., 2019). The shear induced by the intrusion of TS might also increase vertical mixing and lead to a faster erosion of the stratification (Strang and Fernando, 2001). However, the stratification induced by TS can prevent the water column to become entirely mixed in winter. A steady mixed layer can remain if the volume flux provided by TS balances the volume flux of mixed layer deepening (Wells and Sherman, 2001). As a result, the time of complete overturn would be delayed by TS and would only occur when TS stops later in winter (i.e., when $\tau_t > \tau_c$). In the case of Rotsee, TS rarely reaches the lake center and we do not expect a basin-scale effect on the autumn turnover. The effect should be more pronounced in lakes with a larger ratio A_S/A_D, where A_S and A_D are the surface areas of the shallow and deep regions, respectively (Wells and Sherman, 2001).

References:

Ulloa, H. N., Winters, K. B., Wüest, A., and Bouffard, D.: Differential heating drives downslope flows that accelerate mixed-layer warming in ice-covered waters, Geophys. Res. Lett., 46, 13872–13882, https://doi.org/10.1029/2019GL085258, 2019.

Strang, E. J. and Fernando, H. J. S.: Entrainment and mixing in stratified shear flows, J. Fluid Mech., 428, 349–386, https://doi.org/10.1017/S0022112000002706, 2001.

Wells, M. G. and Sherman, B.: Stratification produced by surface cooling in lakes with significant shallow regions, Limnol. Oceanogr., 46, 1747–1759, https://doi.org/10.4319/lo.2001.46.7.1747, 2001.

RC4: *TS is stronger in the summer, but less frequent. As noted, the summer is when this physical process might have the most impact on ecological and biogeochemical processes. Is there a way to compare TS across the months in a more quantitative fashion, for example, the total volume of water flushed in each month?*

AR4: We did not include the flushed volume in the manuscript because its estimation depends on the definition of the flushing period, which is arbitrary (Sect. 2.5, lines 211-212). It is still interesting to compare the seasonality of the daily flushed volume with the seasonality of the occurrence and intensity of TS. We estimated a daily average unit-width volume by normalizing the total volume of water flushed every month by the number of measurement days (Fig. R3.1). The seasonal trend is similar to the occurrence (Fig. 5). This indicates that the weakening of TS from summer to autumn is overcome by the increase of occurrence and flushing duration. Overall, the occurrence of TS is the primary factor driving the seasonality of the flushing in Rotsee, whereas the seasonality of the discharge plays a secondary role. We propose to add Fig. R3.1 to the Appendix.

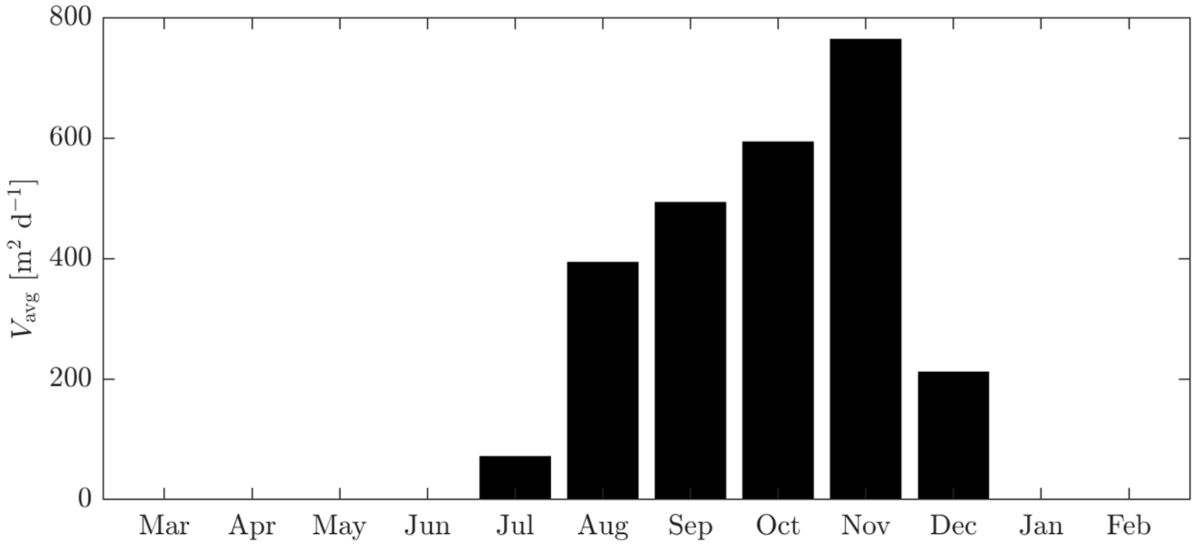

Figure R3.1: Daily averaged unit-width volume flushed by TS every month. Months with less than 10 days of measurements have been removed, as in Fig. 5 of the manuscript.

RC5: *Figure 3d - the contours on the upper right corner look more like an artefact of the contouring than anything that might possibly be real?*

AR5: These dense isotherms are due to the linear interpolation of the strong surface heating captured by the surface thermistor. We will better explain it in Fig. 3d, and we refer to the answer AR9 to Reviewer 1 for more details.

RC6: *Figure 6 - are you forcing the intercept here? From the equations that seems the case (an intercept of 0), but that doesn't look like the best fit line, at least for (b)*

AR6: Yes, we are forcing the intercept to be zero for the four quantities in Fig. 6. We agree that this approach does not provide the best fit but it follows the scaling formulae. The results of the linear fitting with non-zero intercept are:

$U_{avg} = 0.35 \cdot (B_0 L_{ML})^{1/3} - 8 \times 10^{-4}$ m s^{-1},

$U_{max} = 1.22 \cdot (B_0 L_{ML})^{1/3} - 0.006$ m s^{-1},

$q_{avg} = 0.28 \cdot h_{lit} (B_0 L_{ML})^{1/3} + 0.003$ m^2 s^{-1} ,

and $\tau_F = 2.09 \cdot L_{lit} (B_0 L_{ML})^{-1/3} + 2.99$ h.

Note that those results are not significantly different from the scaling with a forced intercept. We will mention the zero intercept in the caption of Fig. 6. The lines 367-368 will now read: *"The equation of the linear regressions (with forced intercept to zero), the coefficient of determination (*R^2*) and the p-value of an F-test (*$p_{val,F}$*) are indicated."*