Cross-shore transport induced by differential cooling in lakes

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Cross-shore flows connect the littoral and pelagic regions of lakes. They can play an important role for the lake ecosystem by transporting heat, dissolved compounds and particles laterally. Here, we study one type of cross-shore flow, driven by **differential cooling** and called ***"thermal siphon"*** (TS).

There is a need for a comprehensive understanding of the conditions required to form thermal siphons, with the objective of better predicting their occurrence and intensity in lakes.

1. **How does TS form?**
2. **How often does TS occur over different seasons?**
3. **How to parametrize the cross-shore transport from the forcing conditions?**

Scan or click on the QR codes to watch videos!

Our approach:

In-situ measurements: Rotsee, LU (2019-2020)

Numerical modelling: 3D (MITgcm) and LES

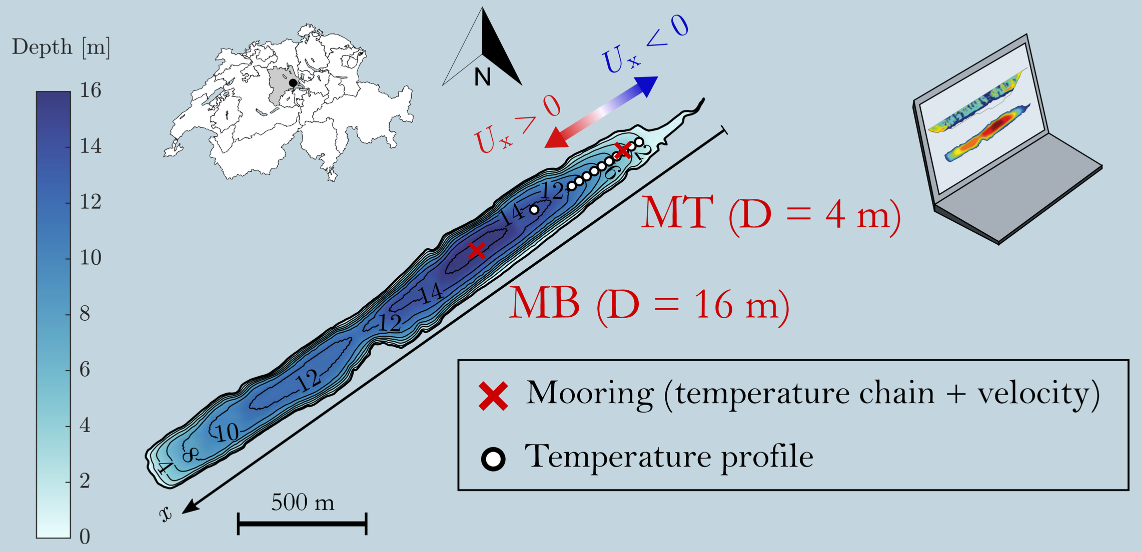

Figure 1 - Bathymetric map of Rotsee

Notations

B_0	surface buoyancy flux [W kg^{-1}]	$\tau_{mix} = f(h_{ML}, B_0, N^2)$	mixing time scale [h]
τ_w	surface wind stress [N m^{-2}]	$\tau_t = f(L_{ML}, h_{ML}, L_p, h_p)$	transition time scale [h]
h_{ML}	mixed layer depth [m]	$\tau_{ini} = \tau_{mix} + \tau_t$	initiation time scale [h]
N^2	squared buoyancy frequency [s^{-2}]	τ_c	duration of the cooling phase [h]
L_p	length of the plateau [m]	U_x	cross-shore velocity [cm s^{-1}]
h_p	depth of the plateau [m]	q_x	cross-shore unit-width discharge [m^2 s^{-1}]
h_{lit}	depth of the littoral region [m]	L_{MO}	Monin-Obukhov length scale [m]
L_s	length of the sloping region [m]	ρ_0	water density [kg m^{-3}]
$L_{ML} = L_p + L_s$	length of the mixed region [m]	ν_z	vertical viscosity [m^2 s^{-1}]

1 Diurnal formation of TS

Diurnal cycle divided into 3 phases:

- Phase 1 (P1), $0 < t < \tau_{mix}$: deepening of the mixed layer
- Phase 2 (P2), $\tau_{mix} < t < \tau_{ini}$: transition period
- Phase 3 (P3), $t > \tau_{ini}$: flushing period (TS)

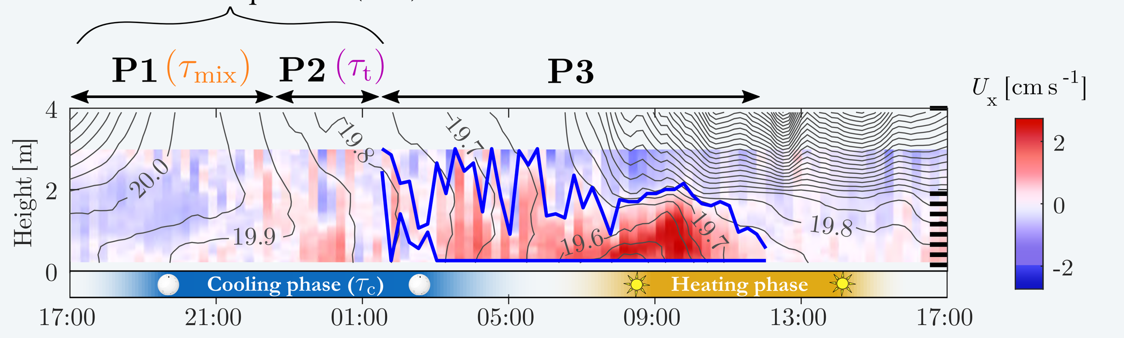

Figure 2 - Cross-shore velocity U_x measured in Rotsee (MT) over one day (August 24-25, 2019) as a function of height above the sediment. Positive (red) values = flow moving offshore. Black lines are 0.05 °C isotherms.

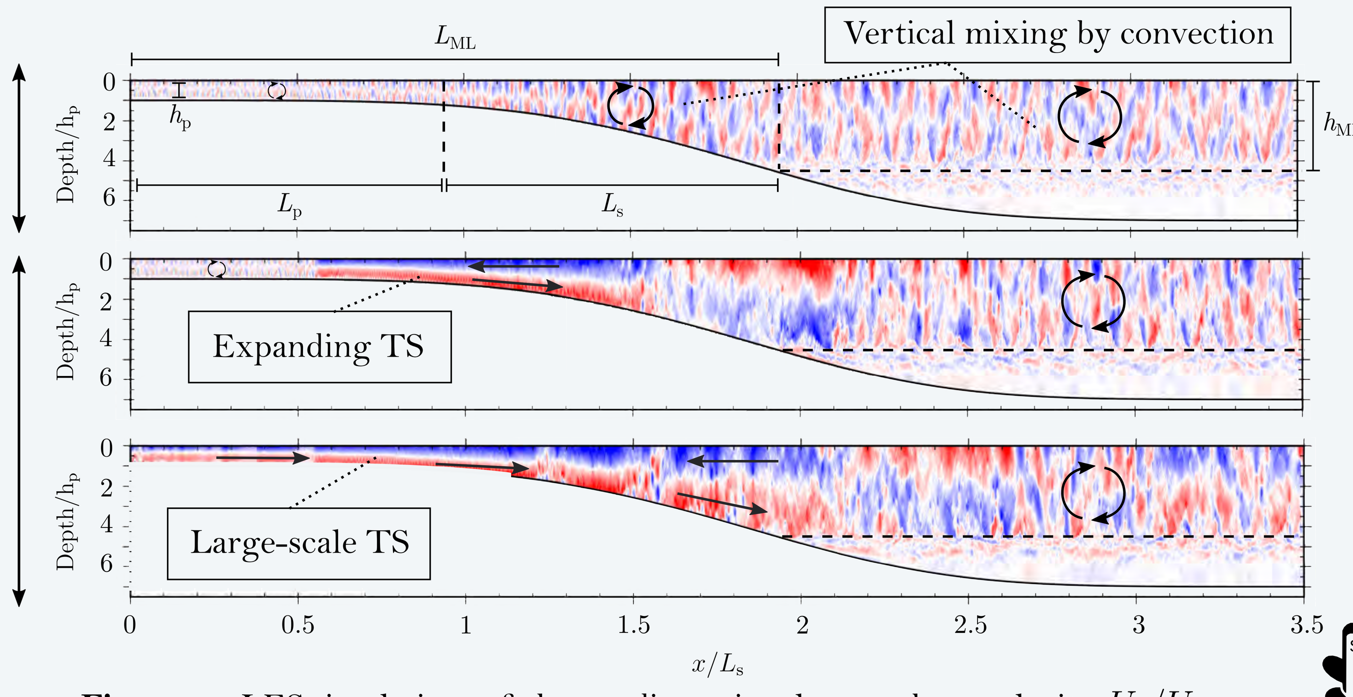

Figure 3 - LES simulations of the nondimensional cross-shore velocity U_x/U_{TS} at three different times, with U_{TS} the velocity scale of TS.

2 Seasonality

Condition of occurrence: $\tau_{ini} < \tau_c \Leftrightarrow \tau_{mix} + \tau_t < \tau_c$

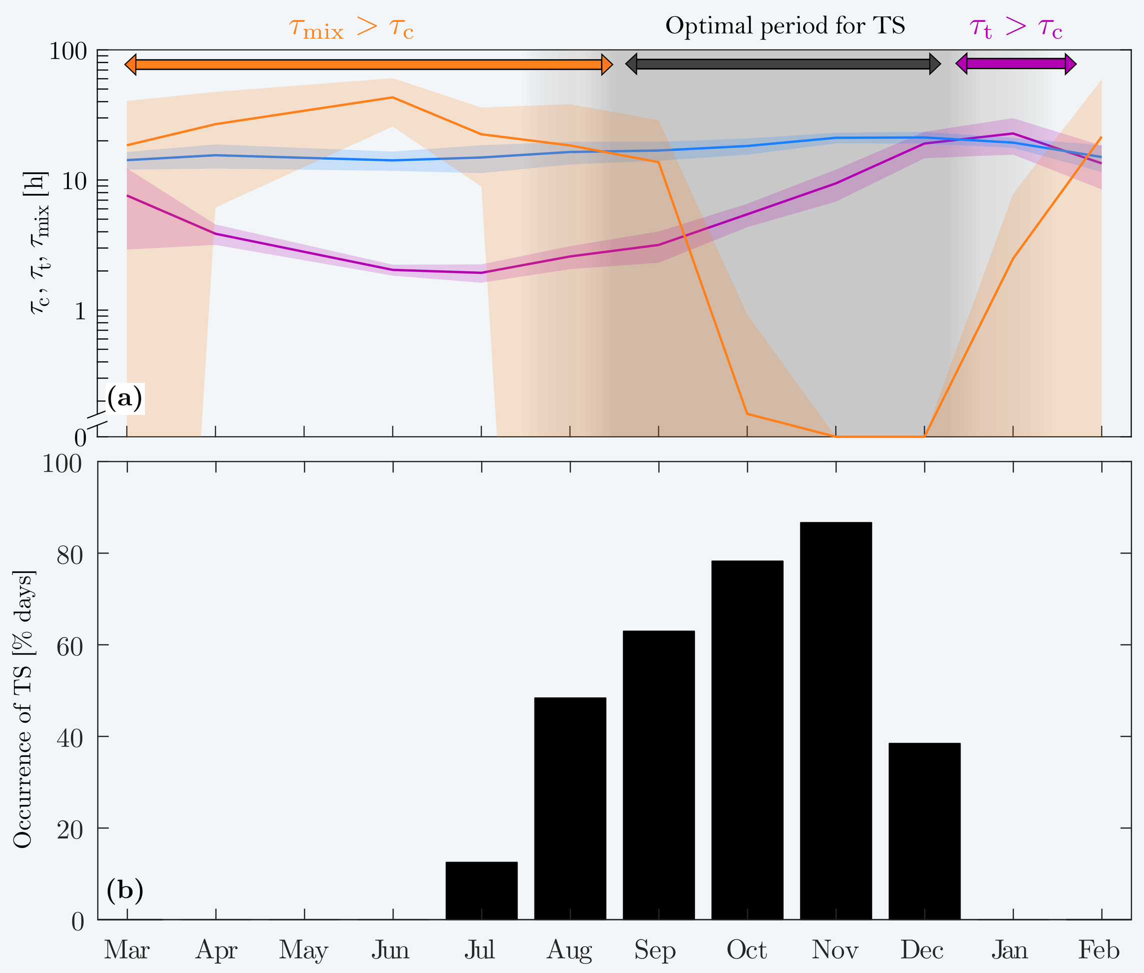

Figure 4 - Seasonal occurrence of TS in Rotsee. (a) Monthly averages of the time scales determining the occurrence. (b) Monthly occurrence of TS measured at MT, expressed as a percentage of days with measurements.

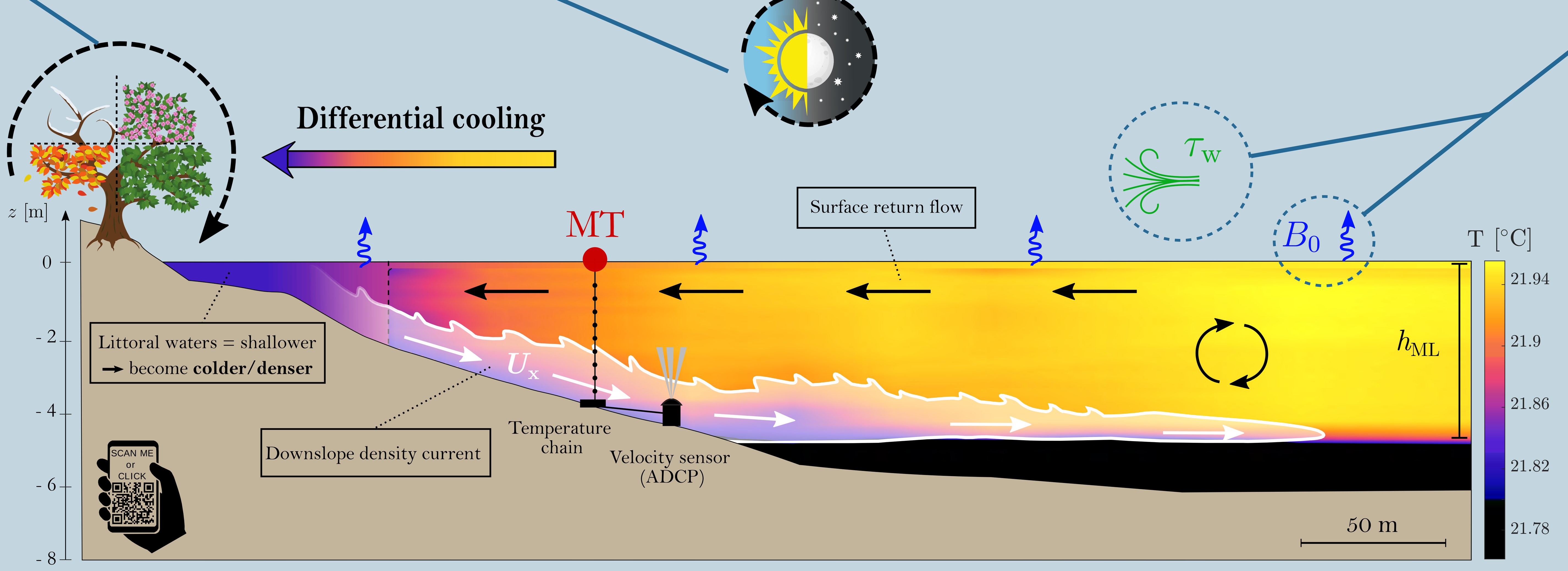

Figure 6 - Data-based schematic of the cooling driven thermal siphon. The temperature field has been linearly interpolated from 11 CTD profiles (Fig. 1) collected in Rotsee on August 22, 2019 (08:20 - 08:45 UTC). The seasonal and diurnal cycle have been designed from https://fr.freepik.com.

3 Transport parametrization

- **Low wind** ($L_{MO}/h_{ML} < 0.1$)
  Transport dominated by convection:
  $q_x \approx q_c$
  with $q_c = 0.3\,(B_0\,h_{ML})^{1/3}\,h_{lit}$
- **Mild wind** ($0.1 < L_{MO}/h_{ML} < 0.5$)
  Enhancement (downwind) or reduction (upwind) of TS:
  $q_x \approx q_c + q_w$
  with $q_w = \frac{1}{27}\frac{\tau_w\,h_{ML}^2}{\rho_0\,\nu_z}$
- **Strong wind** ($L_{MO}/h_{ML} > 0.5$)
  Wind-driven circulation:
  $q_x \approx q_w$

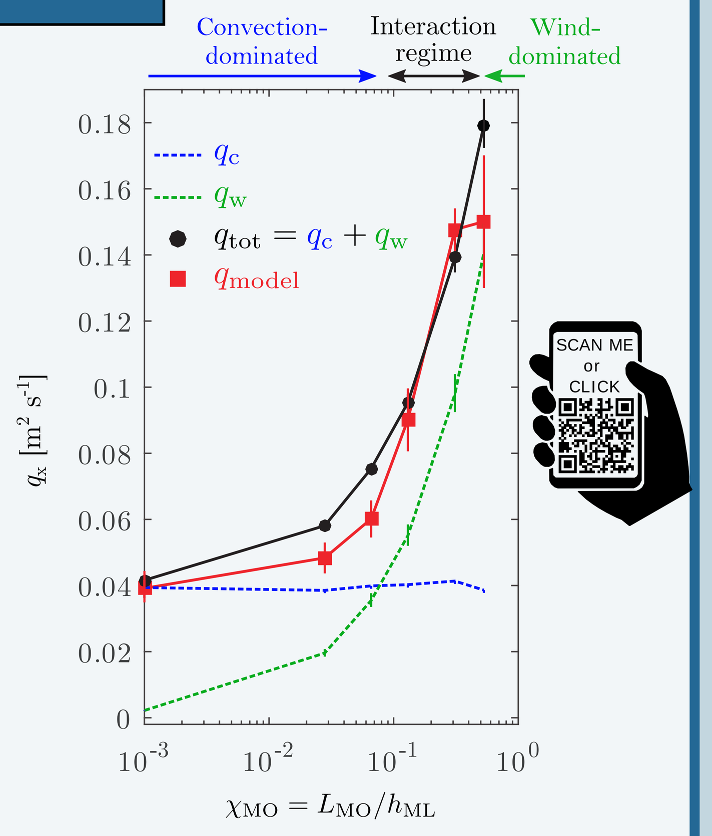

Figure 5 - Modelled and predicted downwind discharge from scaling, as a function of the non-dimensional Monin Obukhov length scale.

Do you want to know more?

About the formation of TS: Ulloa et al., 2021

About the seasonality: Doda et al., 2021 [preprint]

About the wind effects: Ramón et al., 2021 [preprint]

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