Detailed surface energy balance measurements on rock glacier Murtèl (Engadine, Switzerland): New views into the interaction between atmosphere and the active layer

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1 Setting & aim

- Setting: Rock glacier Murtèl located in the Engadine, eastern Swiss Alps, 2630–2730 m asl. (Fig. 1). An active rock glacier (area of 3 ha) with a porous, bouldery active layer (AL) with a thickness of 2–5 m.
- Aim: Determination of the surface energy balance (SEB), in particular the **turbulent fluxes, on the bouldery surface of the ventilated AL/debris mantle**.
- Sensors: PERMOS automatic weather station, PERMA-XT pylon, instrumented cavity (Figs. 2, 3).

Synthesis

- ~90% of the surface net radiation Q^* is re-exported, only 10% is transferred towards the ground-ice table and available to melt ground ice.
- The re-export is mainly via sensible turbulent flux Q_H, secondarily via the latent flux Q_{LE}.
- Water drains rapidly in the debris landform.
- Evaporation becomes moisture-limited in the dry debris mantle a few days after precipitation.
- With less evaporative cooling, temperature gradients and downward heat transfer increase.

> The Murtèl coarse-debris landform is **vulnerable to heat waves and dry spells**.

> Our quantitative process understanding and flux estimates help to **anticipate the reaction of coarse-debris permafrost landforms to climate change** and are **useful for modelling**.

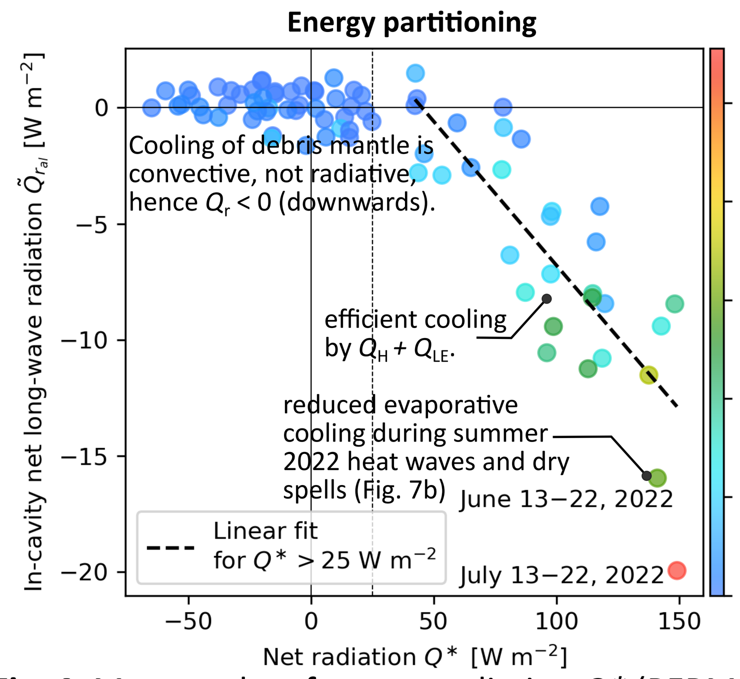


Fig. 4: Measured surface net radiation Q^* (PERMOS) and net long-wave radiation Q_r 1.5 m beneath the surface (Fig. 3; 10-day averages).

Fig. 2: The above-ground automatic weather station: meteo pylon with a CSAT sonic anemometer, a sonic ranger for snow height, hygrometer and pluviometer.

Fig. 3: The below-ground sensor array in a natural cavity, down to 3 m depth, located on a rock-glacier ridge (2658 m asl.). Installed sensors include:
- pyrgeometer (in-cavity net long-wave radiation Q_r in Fig. 4)
- wind speed sensors (Fig. 6)
- thermistors and hygrometers for (T, q) profiles (Fig. 7)

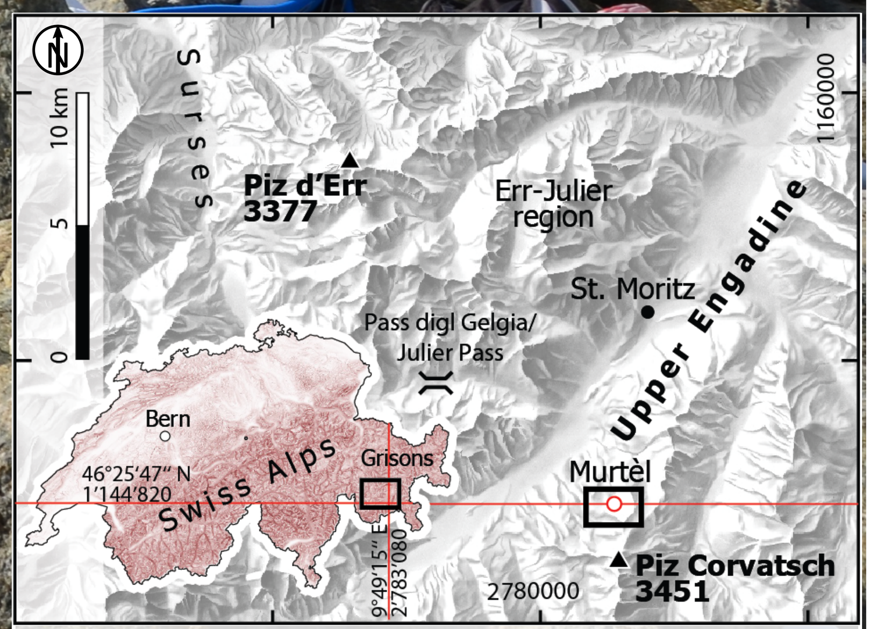


Fig. 1: Location of the rock glacier Murtèl in the Upper Engadine high valley and within Switzerland.

Field view of the coarse debris surface, the meteo pylon and the access to the instrumented cavity. Photograph taken on Oct 11, 2021.

2 Monthly surface energy balance & fluxes

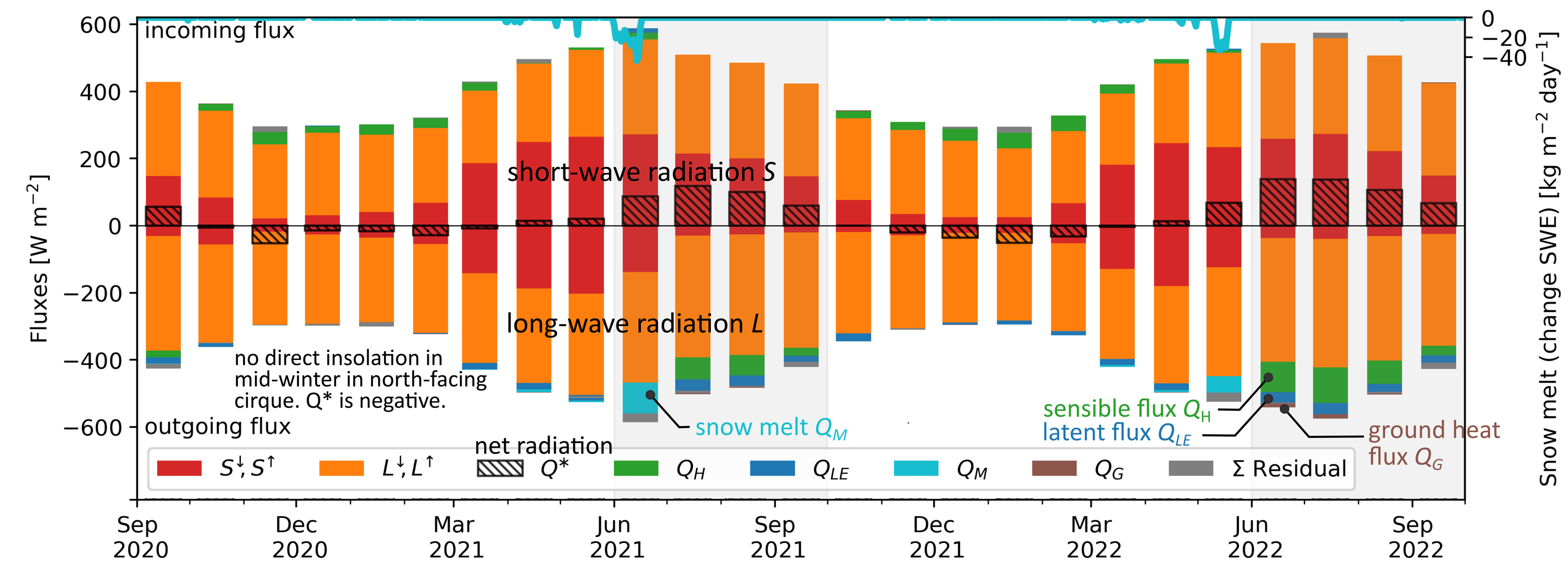


Fig. 5: Estimated surface energy balance (SEB) from Sep 2020–Sep 2022 (Louis (1979)[1] parameterisation).

- SEB dominated by radiation, followed by snowmelt & sensible and latent heat flux (Fig. 5).
- Modelled two-year SEB under seasonally contrasting atmospheric stability: strongly instable in summer, katabatic low-level jets in winter (cf. Fig. 9).

3 Air stratification–wind interactions control AL ventilation

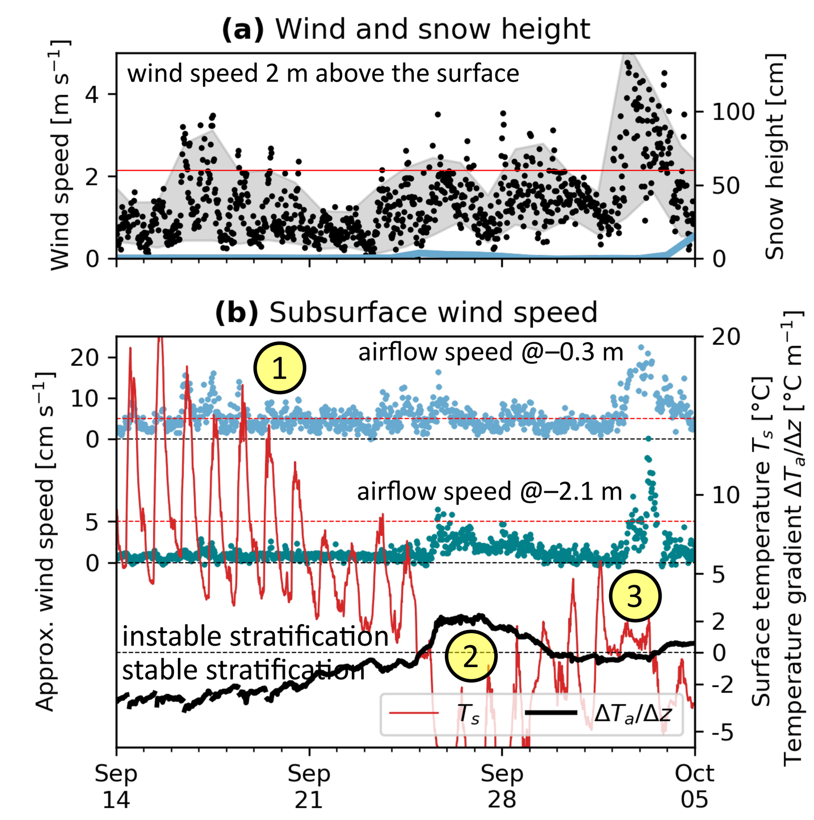


Fig. 6: Zoom-in to the autumnal cooling in 2020 with the different air circulation modes.

- Interplay between subsurface air stratification and atmospheric wind & weather conditions controls the AL ventilation.
- Convective cooling is more efficient than radiative/conductive warming, but occurs less frequently in summer (*thermal diode*).
- Different **ventilation patterns** according to the surface weather and ground thermal regime:

1. Strong diurnal surface heating with **shallow ventilation**: characteristic for summer days. Weak ventilation in deep cavity despite strong winds due to stable air stratification.
2. Rapid surface cooling and destabilization of air column: **buoyancy-driven ventilation**.
3. Vigorous mechanical mixing of isothermal air column by strong winds: **wind-forced ventilation** down to 2 m in the cavity.

4 Summer-time heat and moisture fluxes in the AL

The turbulent fluxes are determined by the **gradients of temperature** T **and specific humidity** q between atmosphere and surface (Fig. 7). We use in-situ temperature and humidity measurements.

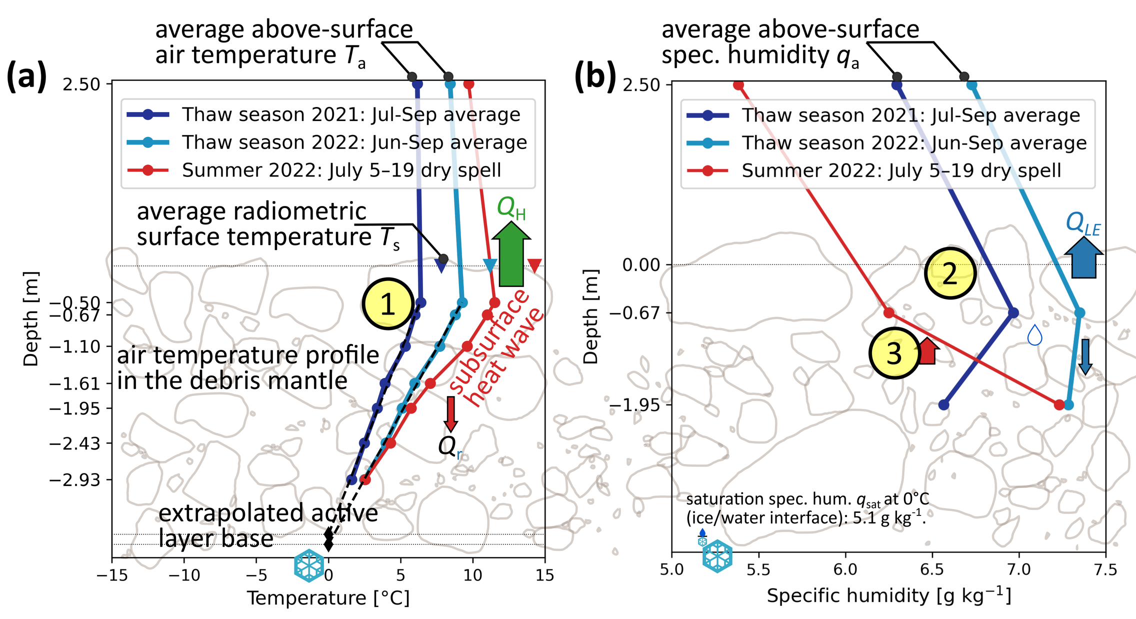


Fig. 7: **(a)** Averaged vertical temperature T and **(b)** specific humidity q profile during the thaw seasons 2021 (wet-cool summer) and 2022 (dry-hot summer).

1. Heat export into atmosphere; turbulent downwards transport impeded by stable stratification.
2. Moisture export from a small, rain-fed reservoir helps cooling the debris.
3. During dry spells: Rapid top-down drying of the AL. Moisture is drawn from progressively deeper AL levels.

5 Modelled turbulent fluxes: results & recommendations

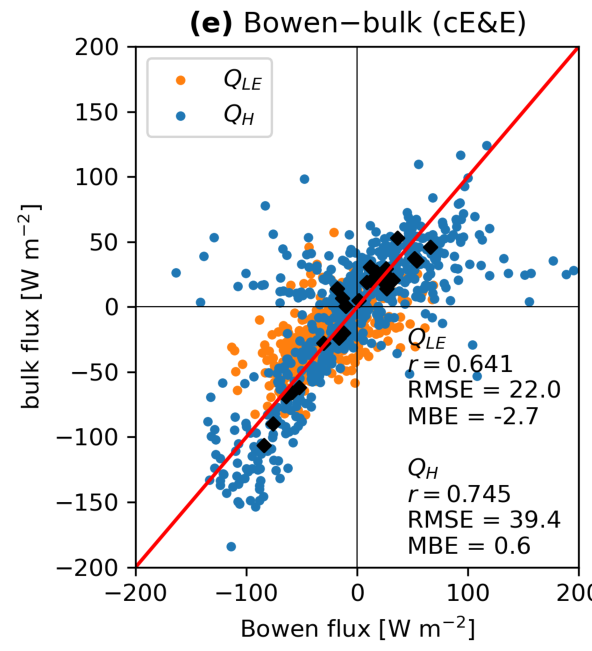
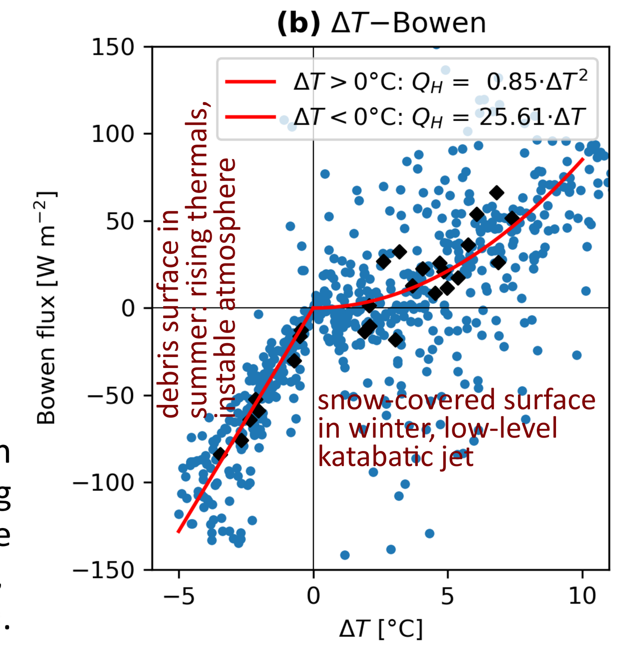


Fig. 8 (left): Bowen flux vs. bulk fluxes (Louis (1979) parameterisation; daily averages).

Fig. 9 (right): Bowen sensible flux vs. driving temperature difference ($\Delta T := T_a - T_s$, daily averages).



- Bowen energy partitioning is a robust, parsimonious approach to model daily turbulent fluxes (Fig. 8). Wind speeds that are difficult to extrapolate in complex mountain terrain are not required.
- The Louis (1979)[1] bulk parameterisation proved faster than the iterative Monin-Obukhov and superior to the commonly used Businger & Dyer stability functions. **We recommend Louis (1979)**.
- The quadratic functional relation between winter-time Bowen flux and driving temperature difference suggests that katabatic parameterisations might be better suited in winter (Fig. 9).

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References
[1] Louis, 1979. A parametric model of vertical eddy fluxes in the atmosphere. Boundary-Layer Meteorol 17, 187–202. https://doi.org/10.1007/BF00117978