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Hydrological significance and dynamics of active rock glaciers under climate change: a case study from the Val d'Ursé, Bernina Range, Switzerland

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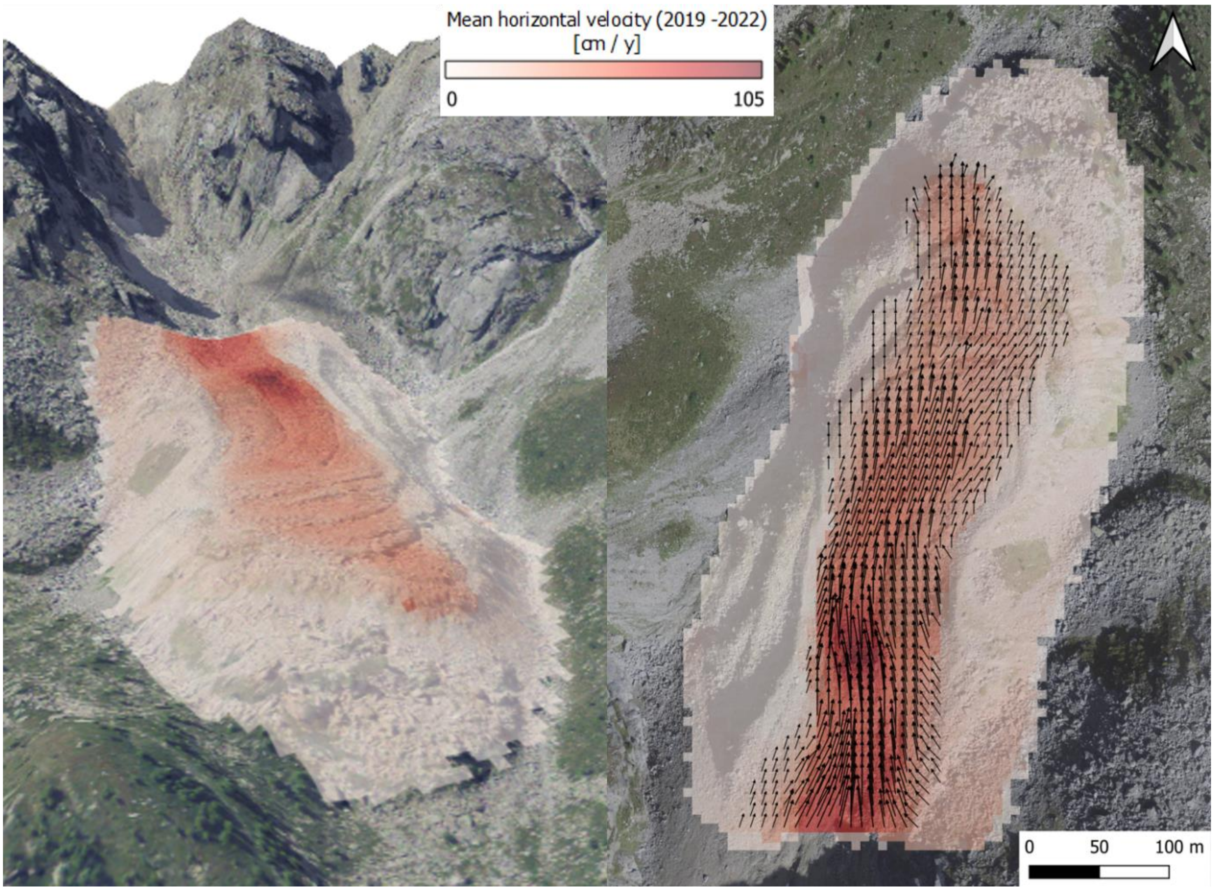
As a consequence of global warming, rock glaciers and freeze/thaw cycles have an increasing influence on the hydrology and water chemistry of alpine environments. We continuously monitored the electrical conductivity and sampled springs and streams in the Val d'Ursé (Bernina Range, Switzerland) between July 2022 and June 2023, with the goal of understanding the importance of the Canfinal rock glacier within the hydrogeological context of this catchment. Using FFT-based digital image correlation on public aerial photos, we determined that this rock glacier is active. The analysis of the recent interannual variations shows that its creep has a velocity of 1 m year^{-1} in the zone that moves the most, and that it has been accelerating since 1990 as a result of rising temperatures with significant accelerations and stabilisations that can be associated with particularly warm and cold summers.

The springs influenced by the Canfinal rock glacier discharge have a distinct geochemical signature, with higher K^+, Na^+, and NO_3^- concentrations and an enrichment in heavy stable isotopes ($\delta^{18}O$ and δ^2H). The higher proportion of these ions reflects the lithology of the debris it contains. These springs are near its foot and within a talus/meadow complex and their discharge undergoes a diurnal dilution/enrichment cycle, the amplitude and phase of which are strongly influenced by the dynamics of the hydraulic head of the fractured aquifer. According to a FFT-based and 1/day segments frequency analysis of their electrical conductivity, this more mineralized water is the main component of these springs. However, the seasonal evolution of the phase lag and amplitude gap of the electrical conductivity in relation to the air temperature indicates that this dilution which begins in the afternoon can be largely attributed to a diurnal freeze/thaw cycle of the rock glacier ice for the spring situated at its foot.

For several years, the Val d'Ursé has benefited from the monitoring of its fractured aquifer's hydraulic head and a stream gauge that provides information on the seasonal dynamics of electrical conductivity and water level in the main stream. Snowmelt appears to be the most important source of recharge. Summer and autumn precipitation cause significant variations in the fractured aquifer, especially once the latter's hydraulic head is already high due to melting snow. Summer meltwater inflows from permafrost, frozen ground, or rock glaciers are also indicated by the electrical conductivity pattern of the Val d'Ursé. However, no isolated and significant contribution from the discharge of the Canfinal rock glacier at the catchment scale was found.

Placing the Canfinal rock glacier in its catchment's larger hydrological context and analyzing the geochemical characteristics of its discharge, particularly their seasonal and

daily evolution, provides useful information on the impact of rock glaciers on water resources in mountain environments. The information gathered, complemented by ERT profiles, was used to establish an initial conceptual model of the hydrogeology of the rock glacier and talus/meadow complex of the Val d'Ursé. We also propose a first step toward incorporating these geochemical parameters into coupled cryo-hydrogeological models using the finite element HEATFLOW-SMOKER code. These will aid in predicting current and future solute fluxes in mountain areas, as well as better understanding the role and future evolution of rock glacier freeze/thaw cycles in the context of climate change.



Average horizontal velocity of the Canfinal rock glacier for the period 2019 - 2022. Vectors represents the horizontal displacement direction and intensity. Average horizontal velocities for three zones of 40x40 m determined from these observations, so all located in the upper part, were compared with climatic indicators for the period from 1990 to 2022.