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Matan Ben-Asher, Florence Magnin, Josué Bock, Jean-Yves Josnin, Sebastian Westermann, Ludovic Ravanel, Philip Deline

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# Hydrological processes and thermal dynamics in high mountain permafrost-affected rock walls

Ben-Asher, M<sup>1</sup>; Magnin, F<sup>1</sup>; Bock, J<sup>1</sup>; Josnin, JY<sup>1</sup>; Westermann, S<sup>2</sup>; Ravel, L<sup>1</sup>; Malet, E<sup>1</sup>; Deline., P<sup>1</sup>.

<sup>1</sup>EDYTEM Lab, Université de Savoie, CNRS, Le Bourget-du-Lac, France.

<sup>2</sup>Department of Geosciences, University of Oslo, Oslo, Norway.

## Abstract

The increased rockfall activity in high Alpine ranges observed during the last two decades is commonly attributed to permafrost degradation associated with atmospheric warming. Although the connection between mountain permafrost warming and rockfall initiation is intuitive and supported by field and lab observations, the physical processes behind it are still poorly understood.

In this study, we focus on the role of hydrologic and thermo-mechanical processes acting in fractures of steep alpine bedrock permafrost. Key challenges of the model scheme are related to the quantification of snow meltwater available for infiltration at different time scales. We combine field observations from a high elevation Alpine site in the Mont-Blanc massif (the Aiguille du Midi, 3842 m a.s.l) with numerical models of surface heat balance and mass transport. We were able to simulate snowmelt between 1959-2020 using the SAFRAN S2M dataset and show that annual snowmelt vary between 0.1-0.4 m/year and that its infiltration potential is limited by the accumulation of an ice crust in the rock-snow interface.

Progress on these issues will help us decipher the governing processes in the degradation of high mountain permafrost and its link with rockfall occurrence.

## Study site – Aiguille du Midi (3842 m a.s.l), Mont-Blanc massif, French Alps.

The Aiguille du Midi lies on the NW side of the Mont-Blanc Massif (Fig. 1). Its summit consists of three granite peaks (North, Central. This part of the Mont-Blanc Massif is composed of porphyritic granite characterized by a N 40° E fault network intersected by a secondary network.



Figure 1: Study site. Aiguille du Midi, Mont-Blanc massif, French Alps

A tourist cable car runs from Chamonix to the north peak, where galleries and an elevator are carved in the rock mass and provide year-round access to the otherwise extreme and inaccessible environment.

## High altitude experiment – real time monitoring of snow melt infiltration

The man-made galleries in Aiguille du Midi give rare access to the interior of the rocky peak and to the fractures system. In the spring of 2022, we installed an experimental system to monitor real-time snowmelt. The system is located under a steep north-facing slope. We inserted two different fluorescent dyes in two snowpack locations above the monitored fracture (Fig. 2). The system is equipped with sensors for luminescence, temperature and conductivity.



Figure 2A: Snowmelt water monitoring system



Figure 2B: Insertion of fluorescent dye in the snowpack above the gallery

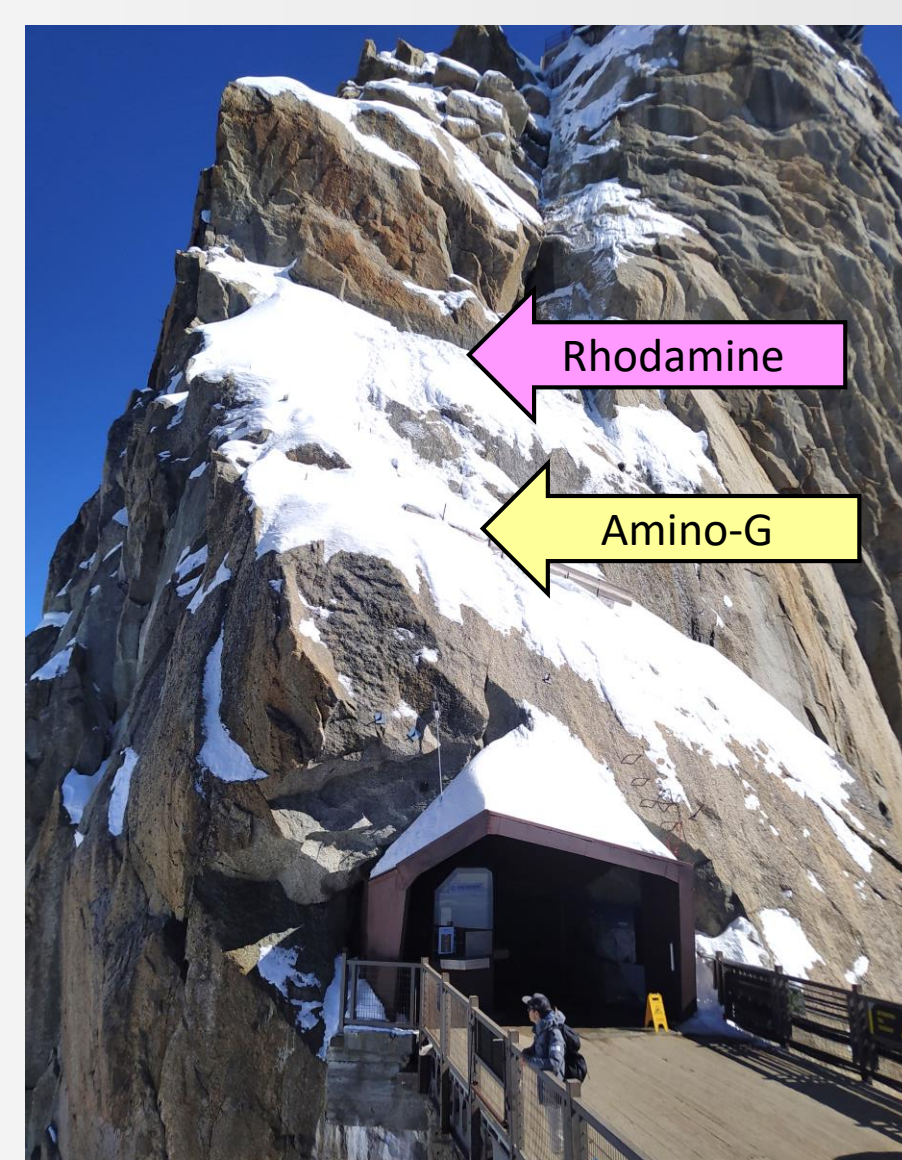


Figure 2C: Upper and lower snow packs above the gallery and the type of different dyes used

## Numerical modelling – water equivalent snowmelt

We used the CryoGrid community model toolbox (Westermann et al., 2022) to simulate 62 years of 1D ground thermal regime and ice/water balance to estimate the availability of surface water and its potential for infiltration in rock fractures (Fig. 4).

## Monitoring active layer dynamics with three 10 m deep boreholes

Three boreholes were drilled in 2009 to a depth of 10 m from the rock surface, in three different aspects (SE, E, N).

## Temporal and spatial analysis of snow depth

We produced two 3D photogrammetric point cloud models of the slope rock surface. One with minimal snow cover in October 2021 (Fig. 3A) and another with substantial snow cover following heavy snowfall in January 2022 (Fig. 3B).

We also mounted timelapse cameras to monitor snow depth using a permanent measurement poles (Fig. 3C).



Figure 3A: SE face of Aiguille du Midi with minimal snow cover.



Figure 3B: SE face of Aiguille du Midi with substantial snow cover.



Figure 3C: Snow depth measurement pole

## Snowmelt and water availability for infiltration

Model results of the snowmelt in our study site range between 0.1-0.4 m/year (Fig. 4A). However, we suggest that the formation of an ice layer at the base of the snowpack prevent infiltration in spring months, and the actual snowmelt that is available for infiltration range between 0.01-0.2 m/year and occurs mostly between June-September (Fig. 4B).

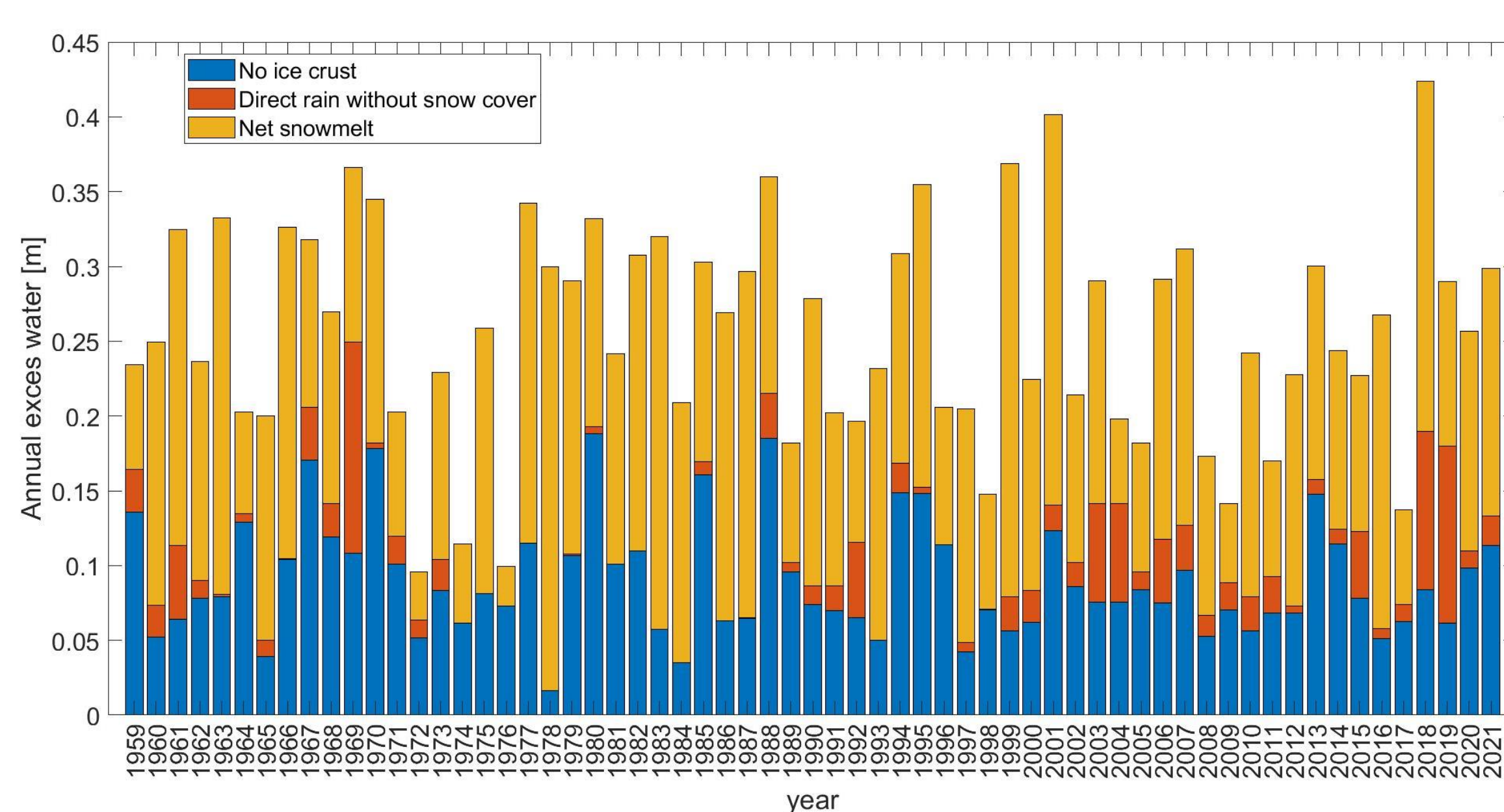


Figure 4A: Modelled annual excess surface water (m)

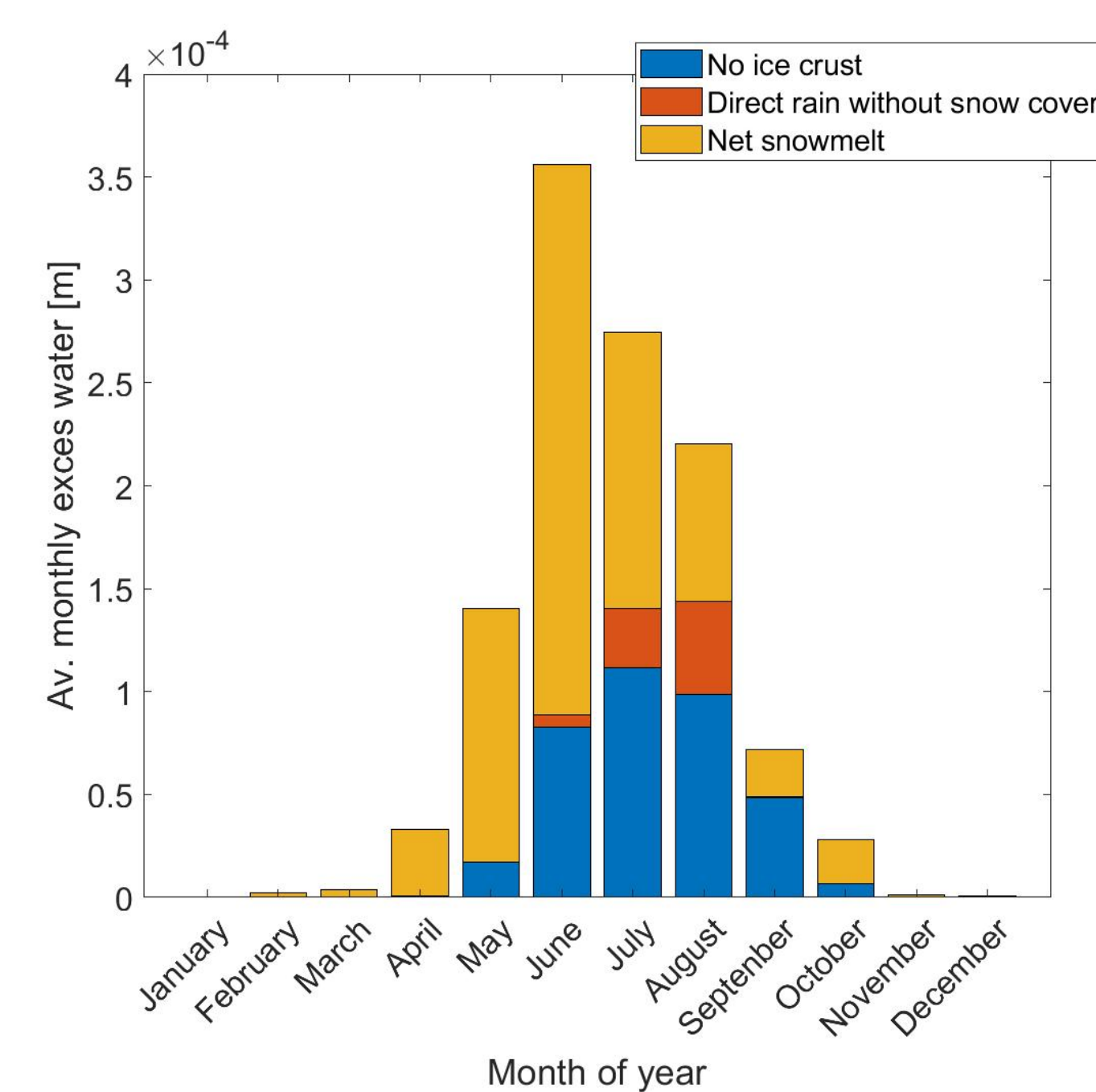


Figure 4B: Average modelled monthly excess surface water (m)

## Initial results from snowmelt monitoring

We documented 3 periodic events of snowmelt in May-June 2022, which correspond to periods of high air temperatures. The water show high concentration of amino-G dye that we inserted in early May 2022 in the snowpack that is directly above the gallery. We see no indication of the Rhodamine dye that we inserted in the higher snowpack. Results show a sharp increase and then a moderate decrease in fluorescence that may indicate a low rate input of water from another source, without dye.

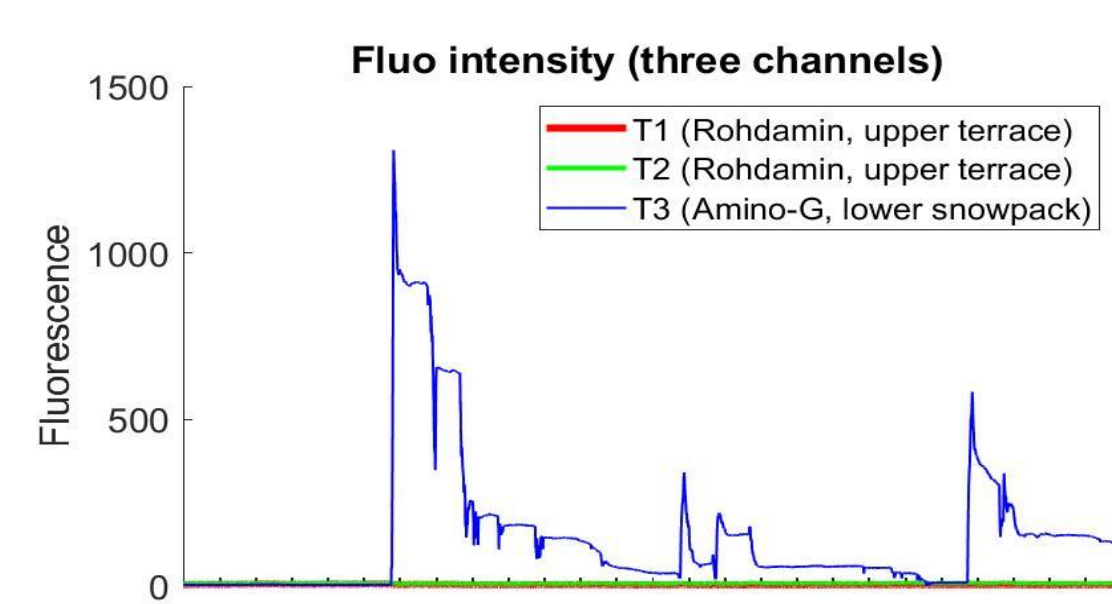


Figure 5A: Water fluorescence intensity at three wavelength channels (T1, T2, T3) which corresponds to the two dyes we used: amino-G and Rhodamine

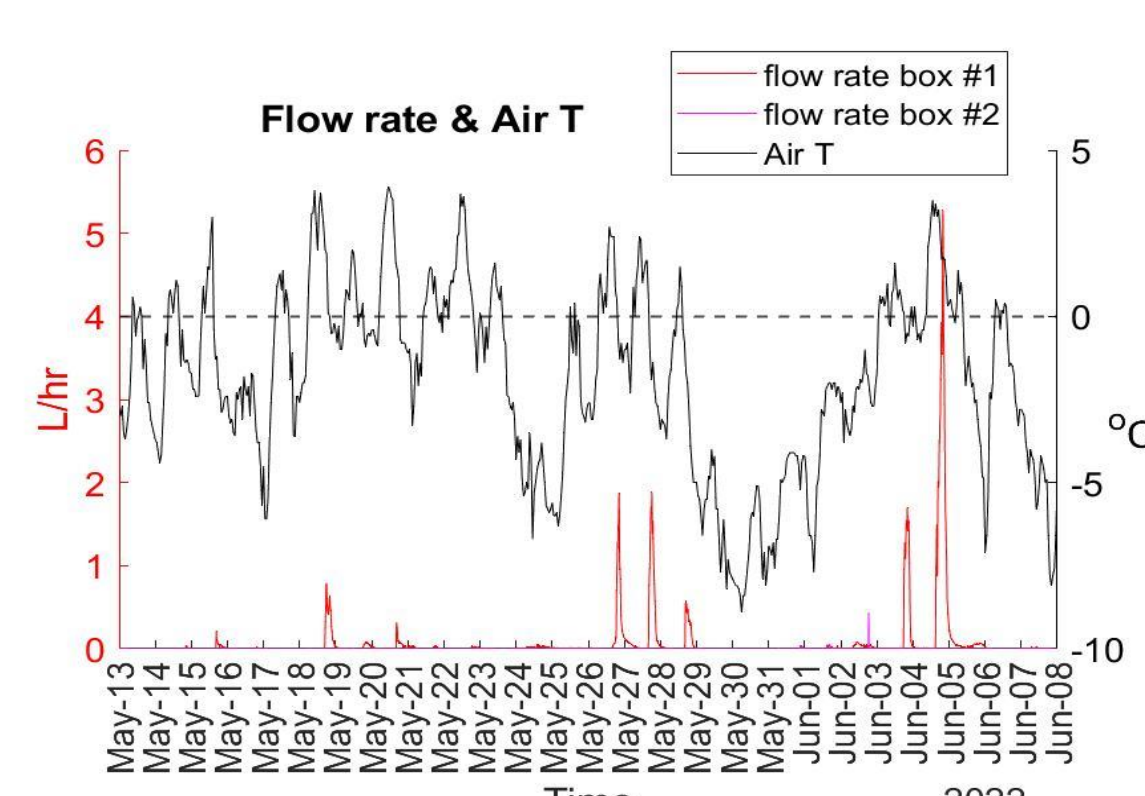


Figure 5B: Water flow rate (red & pink, left y axis) and air temperature (black, right y axis)

## North vs. South

South facing rock wall gets 37 % more effective snowmelt in comparison with north facing (Fig. 6A). While on north face effective snowmelt duration is mostly limited to June-August, on the warmer (Fig. 6B) south face the duration ranges between May-October

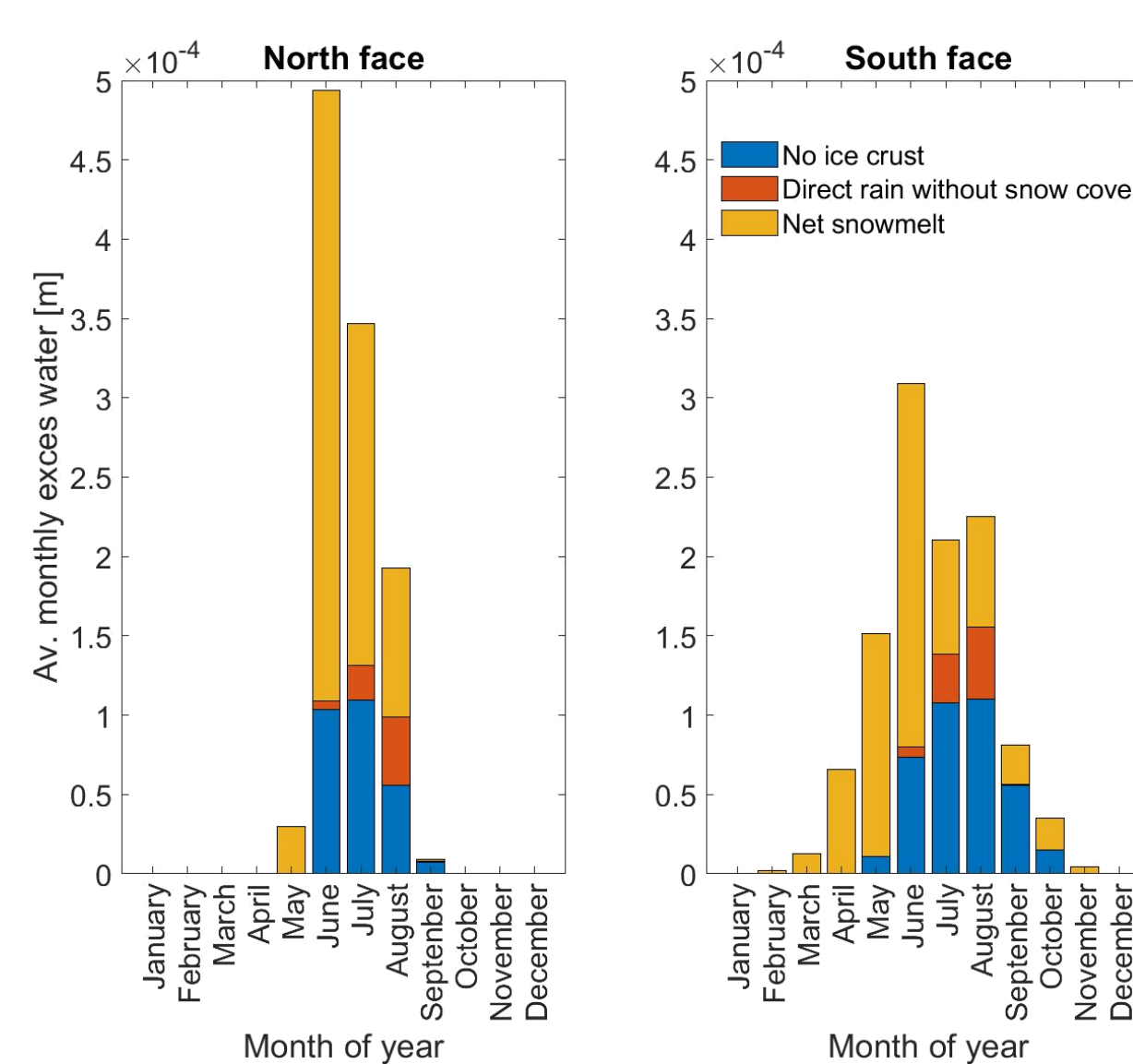


Figure 6A: Average modelled monthly excess surface water on north (left) and south (right) facing rock wall

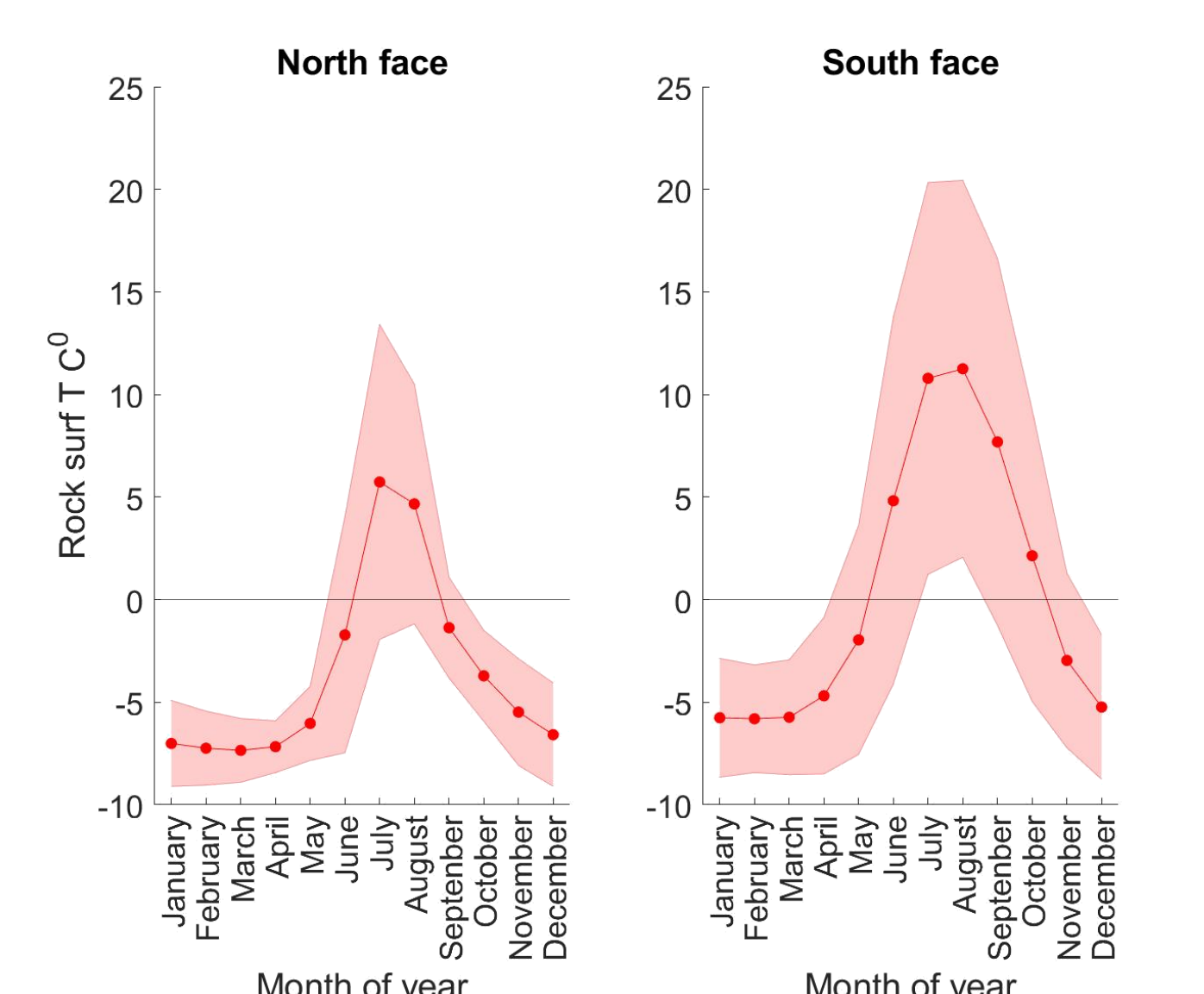


Figure 6B: Average modelled monthly rock surface temperatures of north (left) and south (right) facing rock wall and range of ±σ

## Varying elevation

The SAFRAN S2M (Vernay et al., 2022) meteorological data set provide a resolution of 300 m in elevation. We used this dataset with our calibrated model to analyze the variation of excess surface water with changing elevation. We found that rainfall becomes a dominant water source at elevations of 3600 m a.s.l and lower.

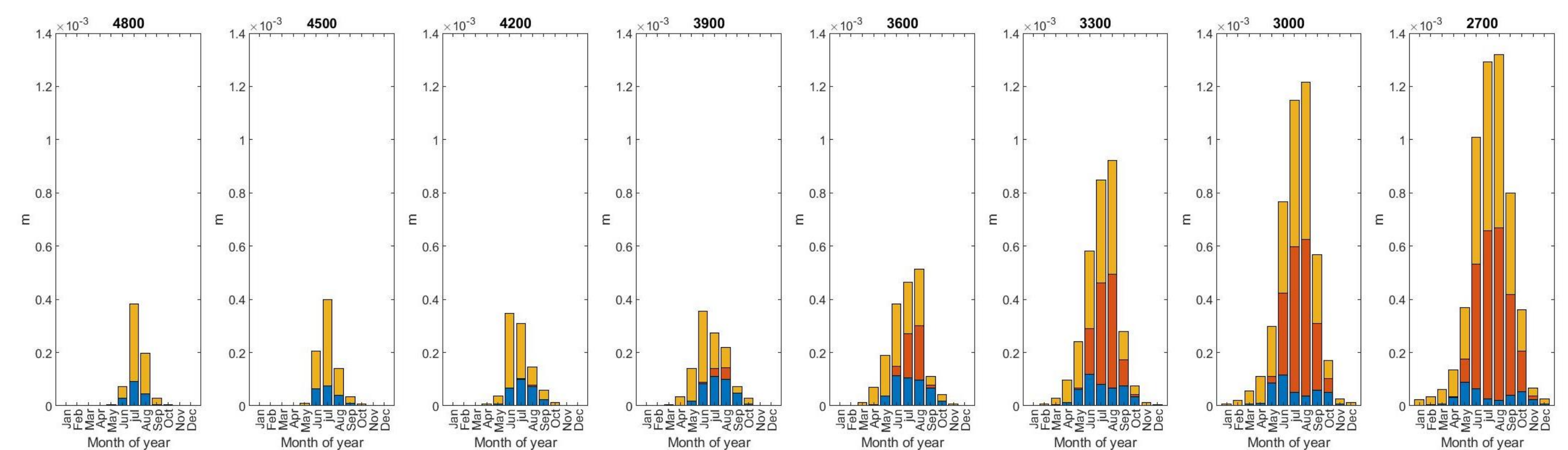


Figure 7: Average modelled monthly excess surface water (m) at elevations of 2700 – 4800 m a.s.l

## Further work

We plan to use our results as forcing data in a numerical finite element model of subsurface hydrological and thermal processes implemented with the FEFLOW® program (DHI-WASY) to examine the influence of water infiltration on the thermal dynamics and degradation of mountain permafrost. We will integrate our results with information on rock temperatures using conductivity and induced polarization tomography data from an existing system that we installed. We expect this study to give unprecedented constrains on the availability of water for infiltration in high mountain rock walls and gain better understanding on their role in permafrost degradation and mechanical stability of steep fractured rock walls.

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