

Estimating surface water availability in high mountain rock slopes using a numerical energy balance model

Matan Ben-Asher¹, Florence Magnin¹, Sebastian Westermann², Josué Bock¹,
Emmanuel Malet¹, Johan Berthet³, Ludovic Ravanel¹, Philip Deline¹.

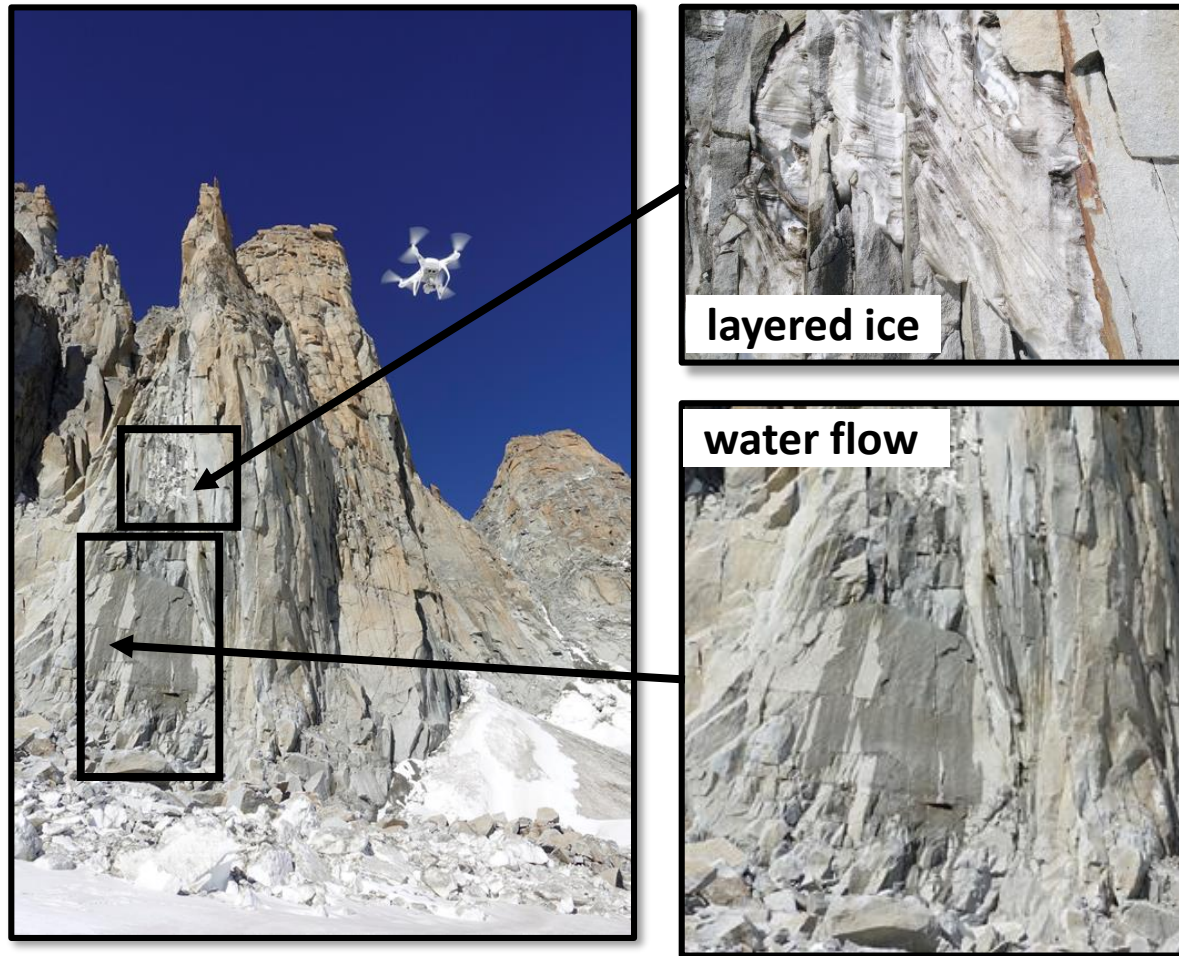
¹EDYTEM lab., Université Savoie Mont Blanc, CNRS, Le Bourget-du-Lac, 73376, France.

²Department of Geosciences, University of Oslo, Oslo, Norway.

³Styx 4D, Le Bourget du Lac, France.

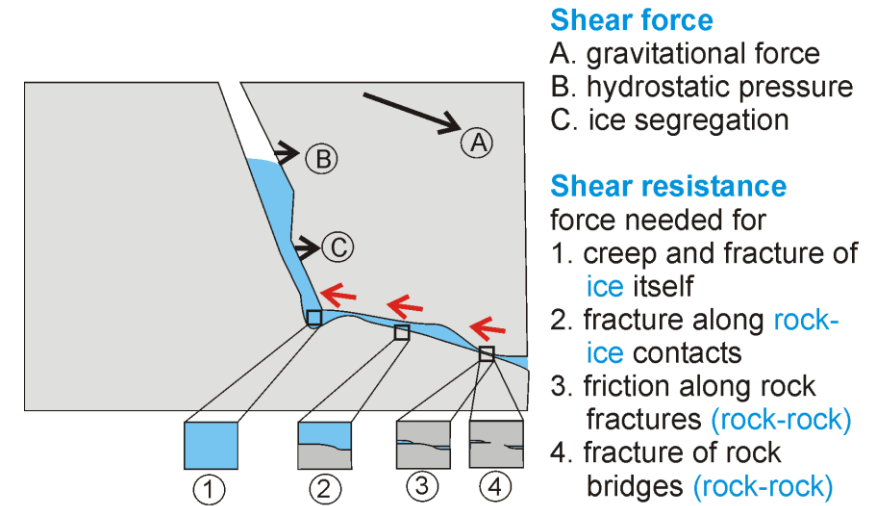


Water in steep high mountains



L. Ravanel

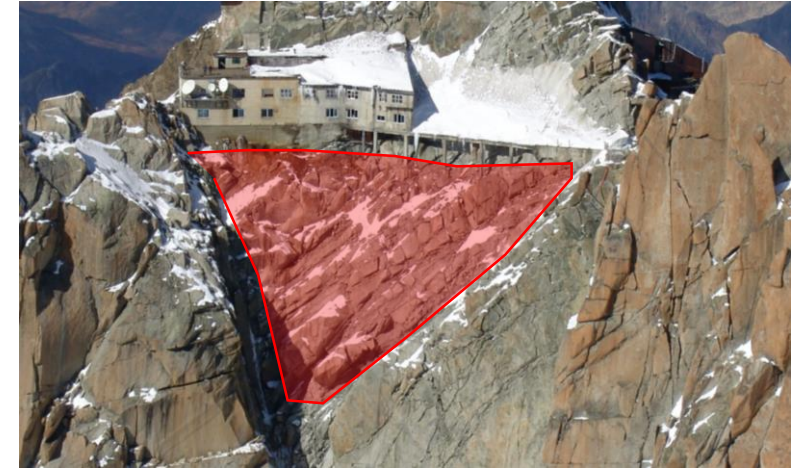
Mechanical + thermal effect



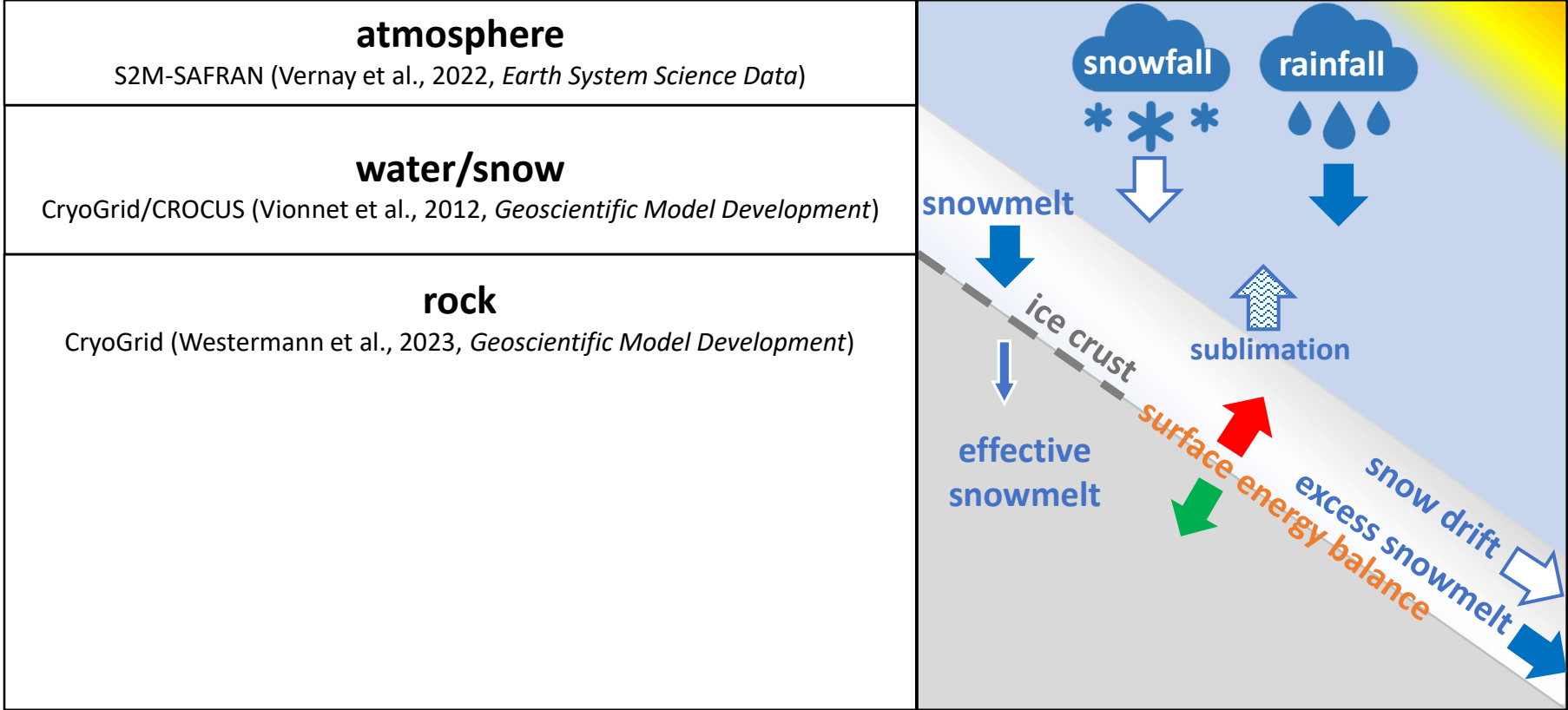
Krautblatter et al., 2013

Rockfall car on the Trident du Tacul rock fall (Mont Blanc), 26th September 2018.

'Natural laboratory' - Aiguille du Midi (3842 m), Mont Blanc massif



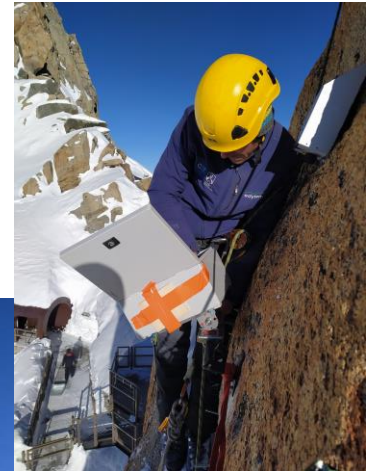
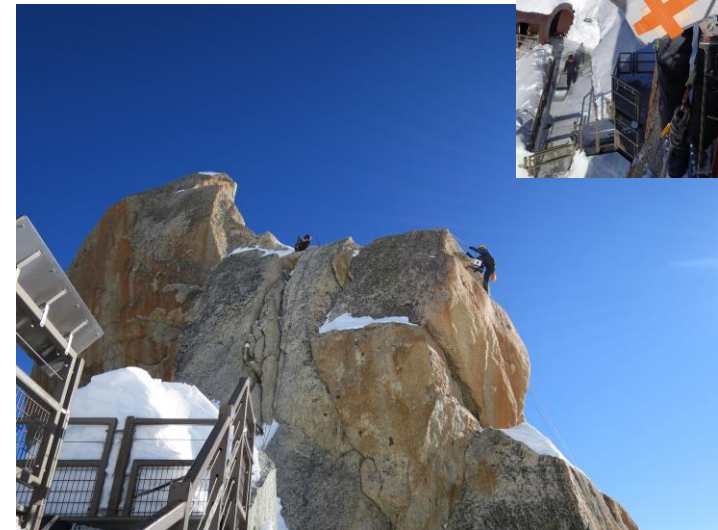
Numerical model setup (CryoGrid)



Field measurements

Go see posters #A1 and #A66 for more

4 × 10 m deep boreholes installed in 2009
Time lapse camera
Snow accumulation measurements poles
Surface temperature: i-buttons
3D high resolution surveys using a drone

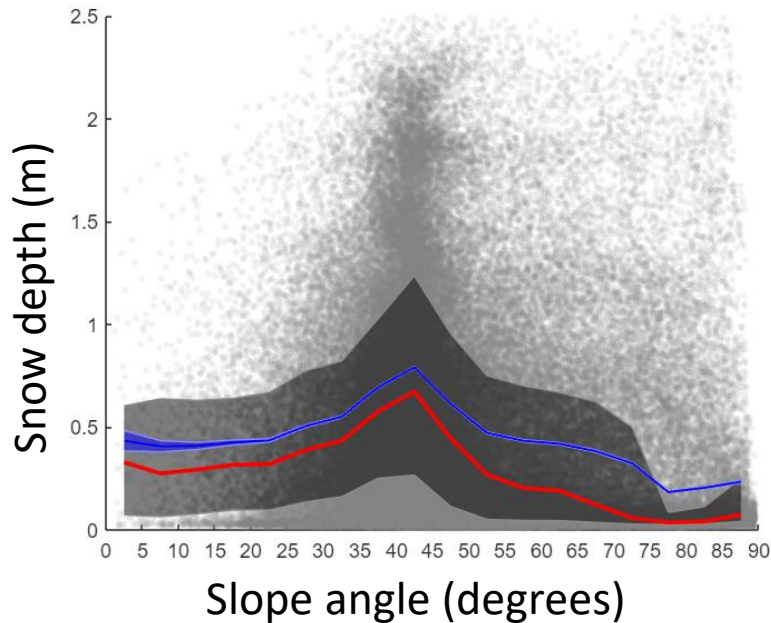
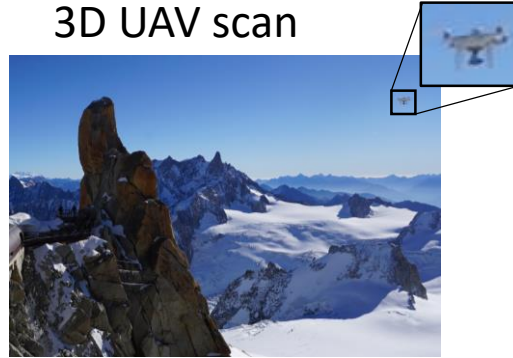


Results – snow accumulation

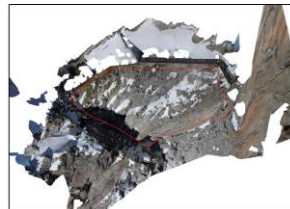
Slope angle

Snow accumulation decreases from 80 cm to 0 cm between slope angles 40°-70°

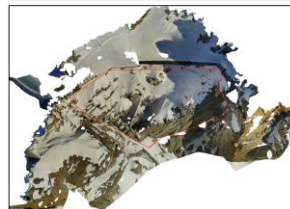
3D UAV scan



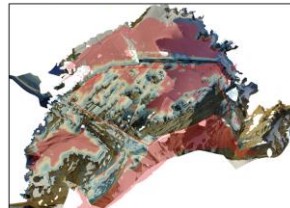
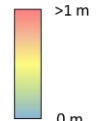
October 2021 UAV image



January 2022 UAV image

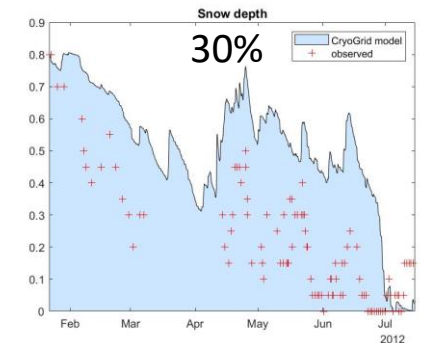
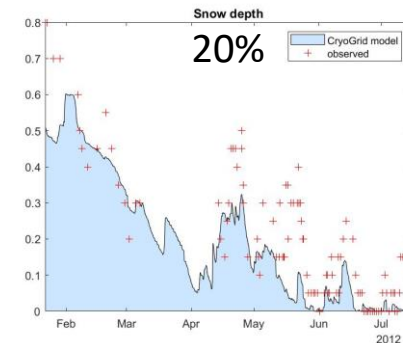
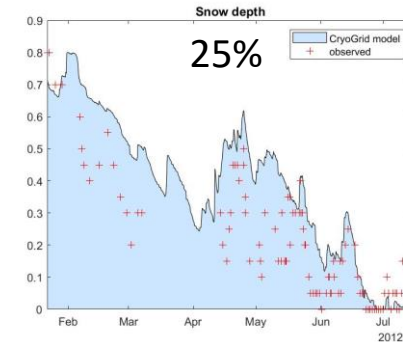


snow thickness

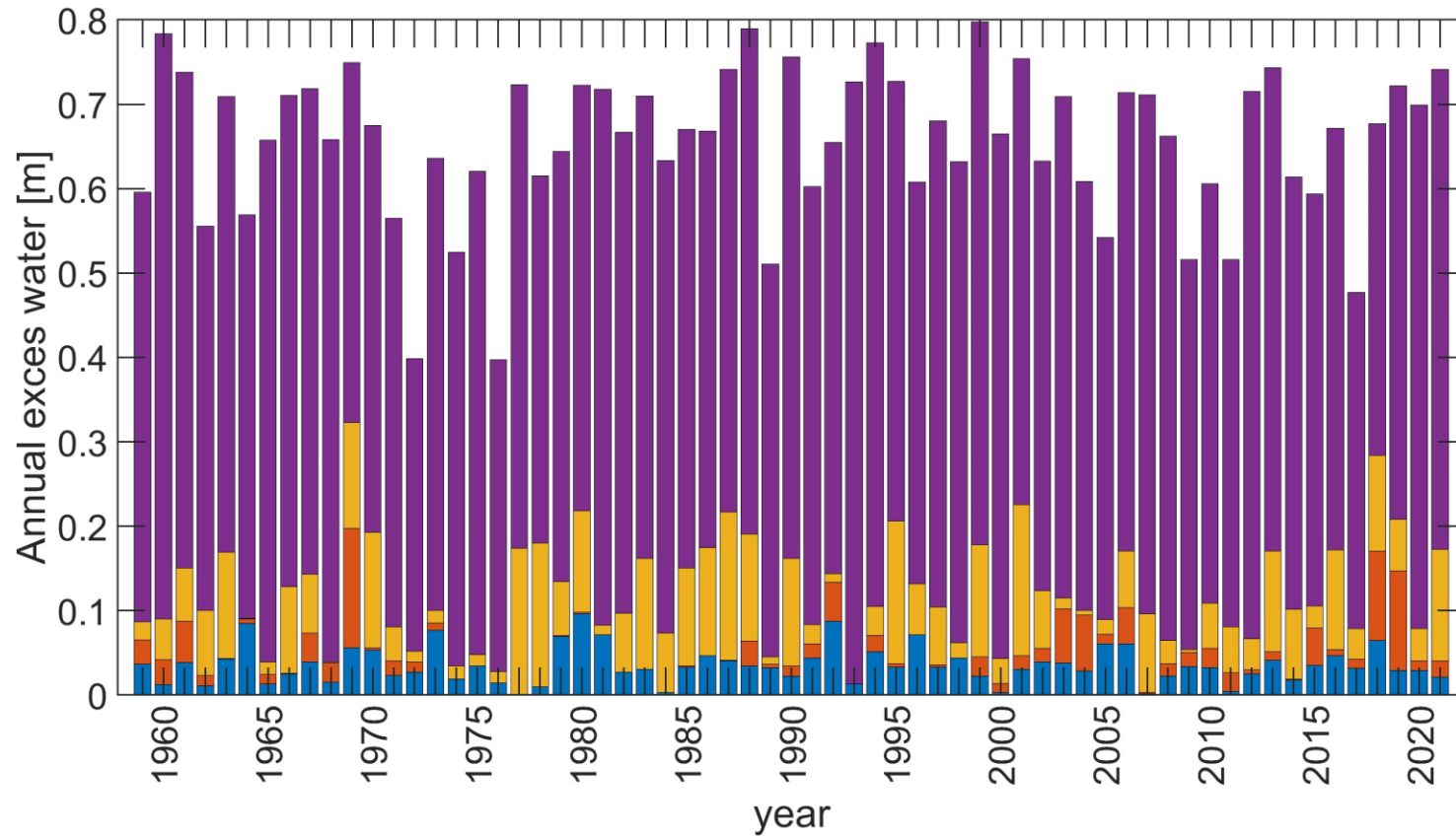


snow accumulation factor

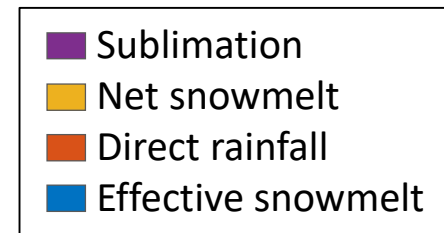
Only ~25% of the snowfall accumulates in our study site (slope angle 45° -55°)



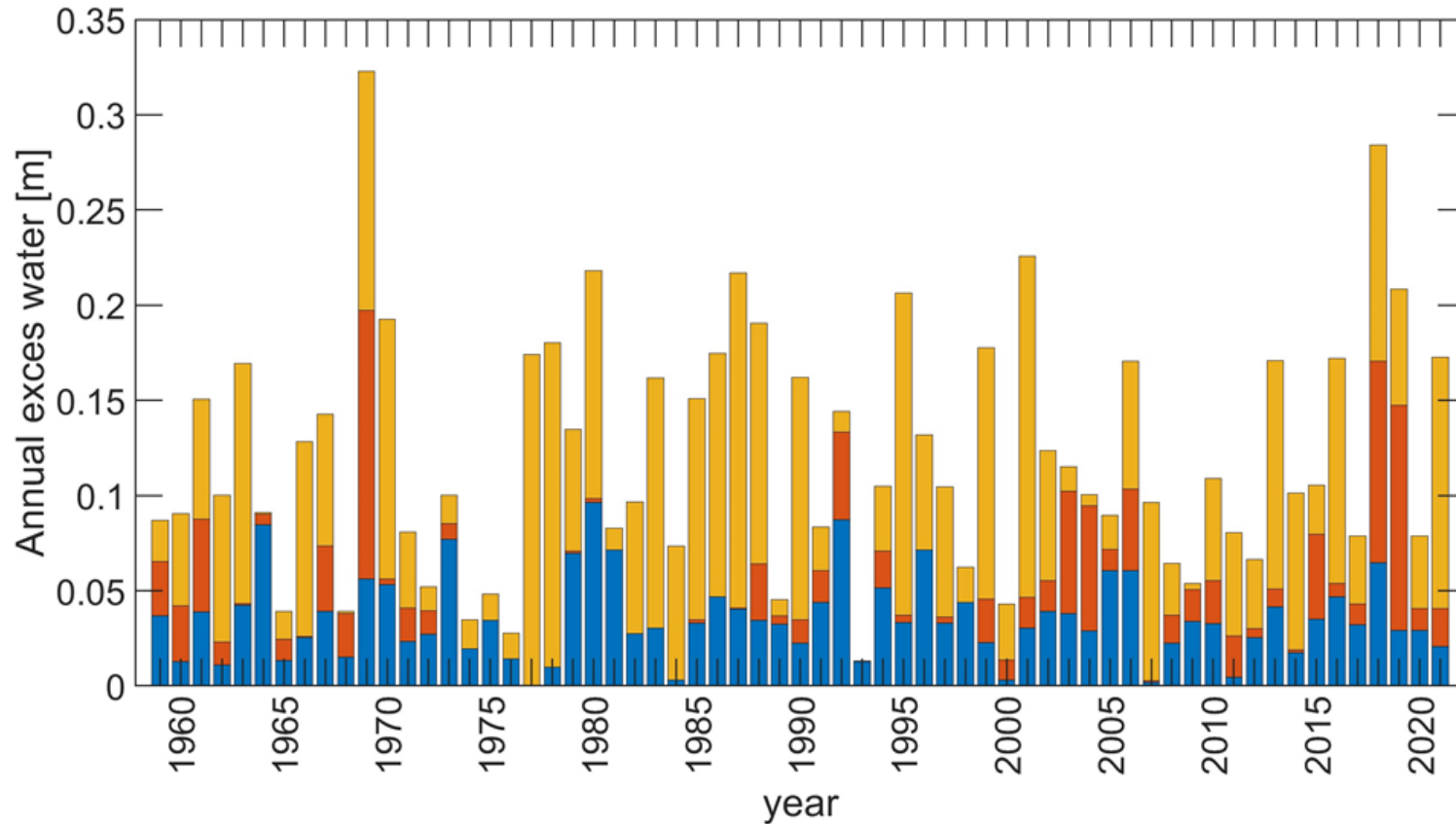
Model results – Annual water balance



High sublimation rate



Model results – Annual water balance

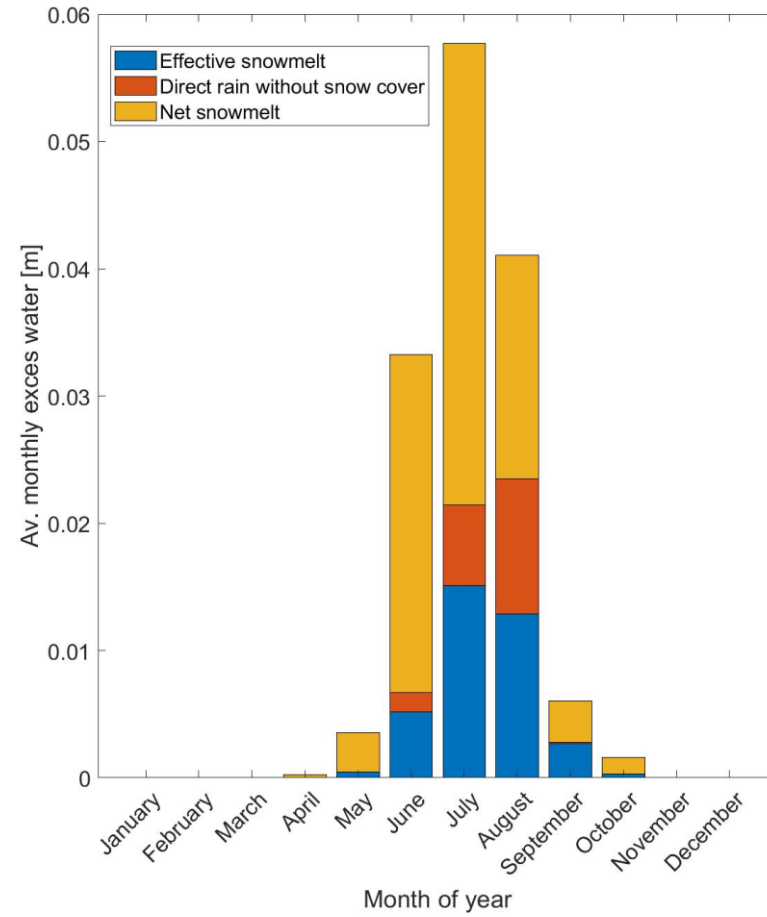


High annual variability
of water availability

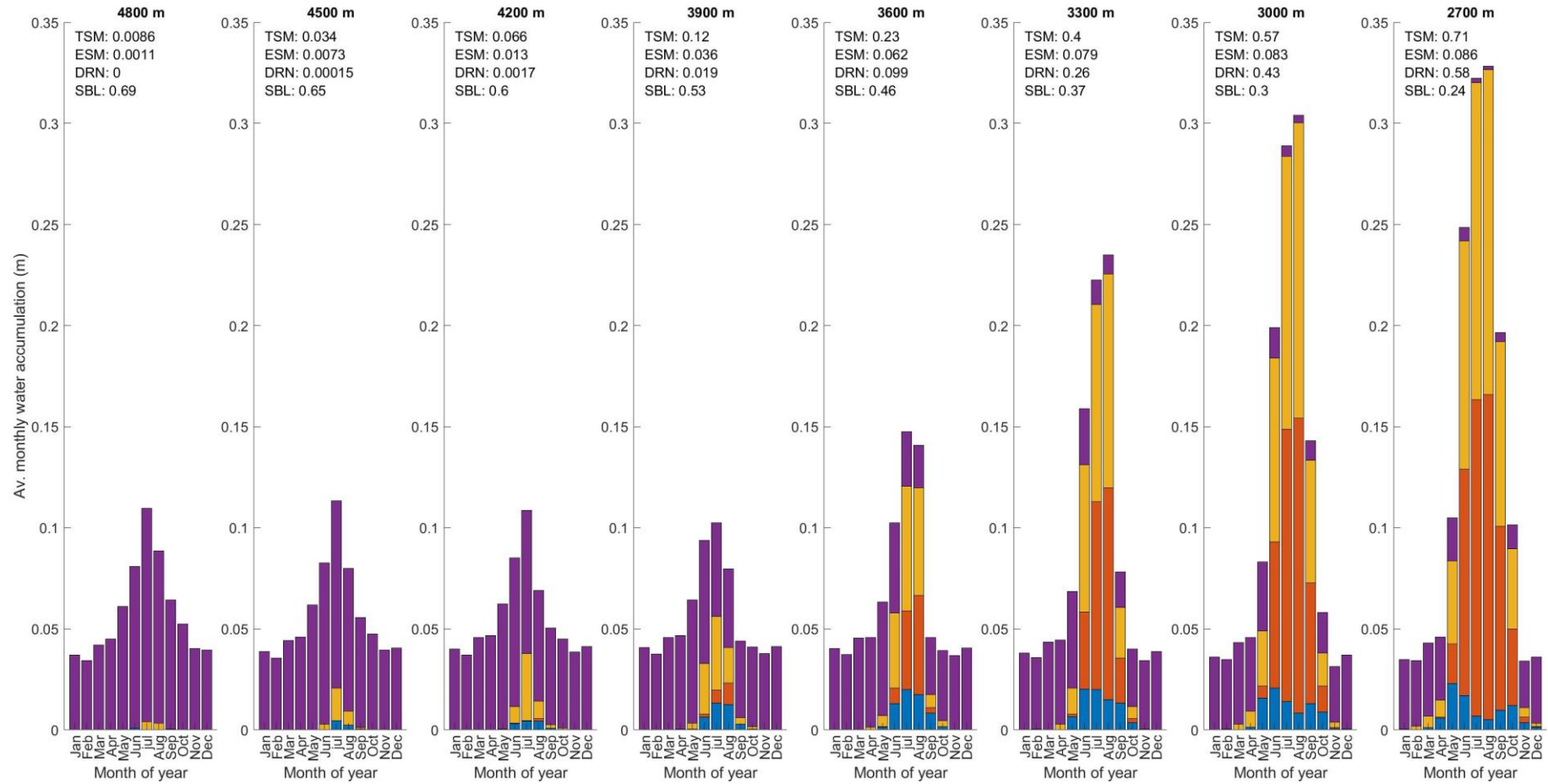
Ice crust at snowpack – rock interface



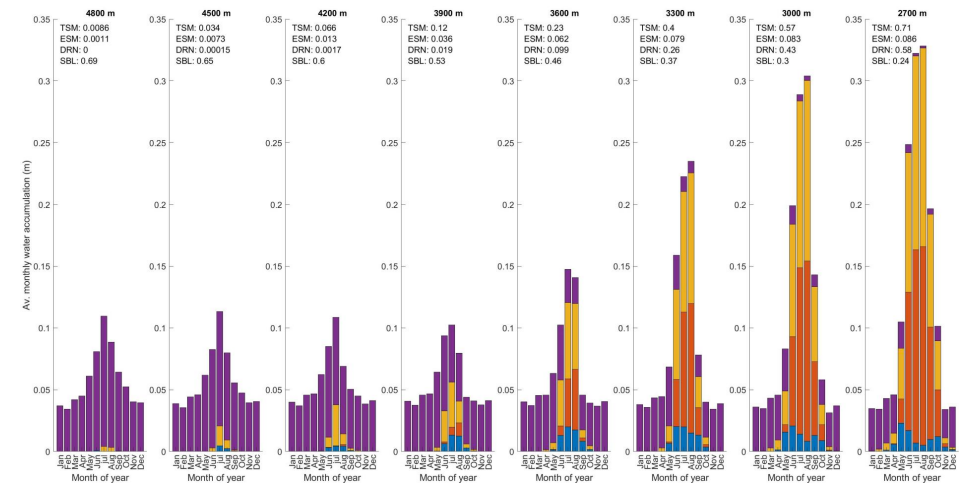
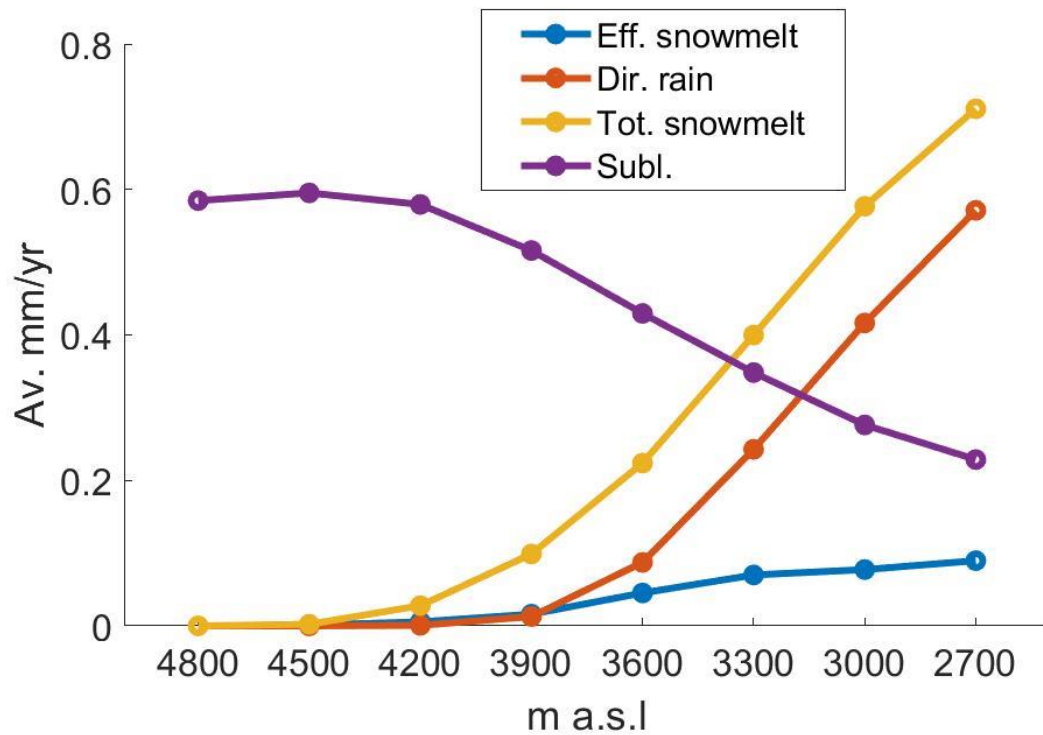
Results – Water availability during the year



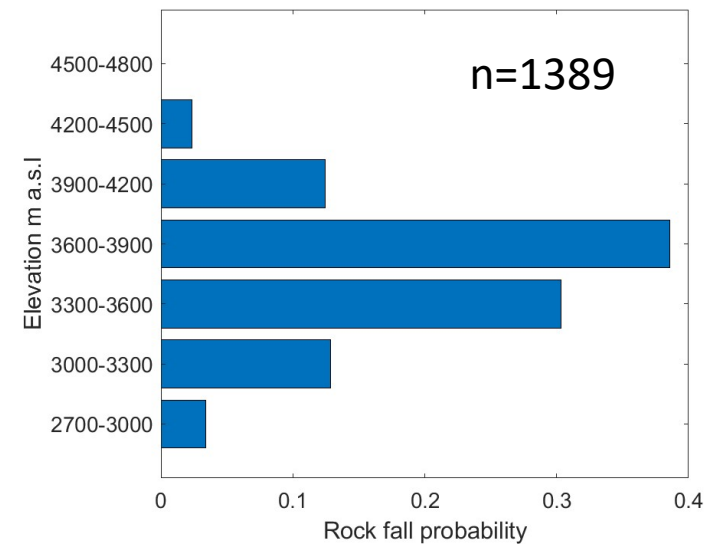
Model results – Changing elevation



Results – Changing elevation



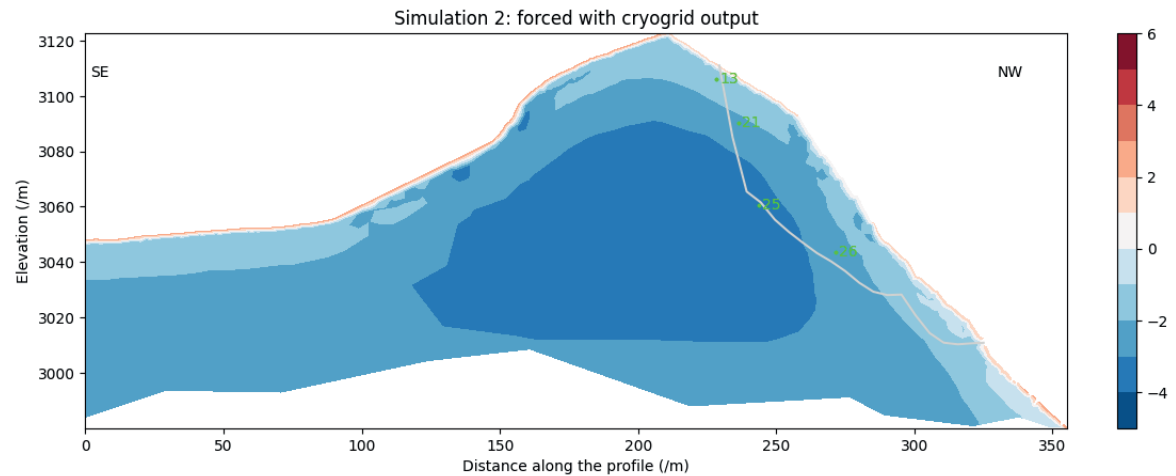
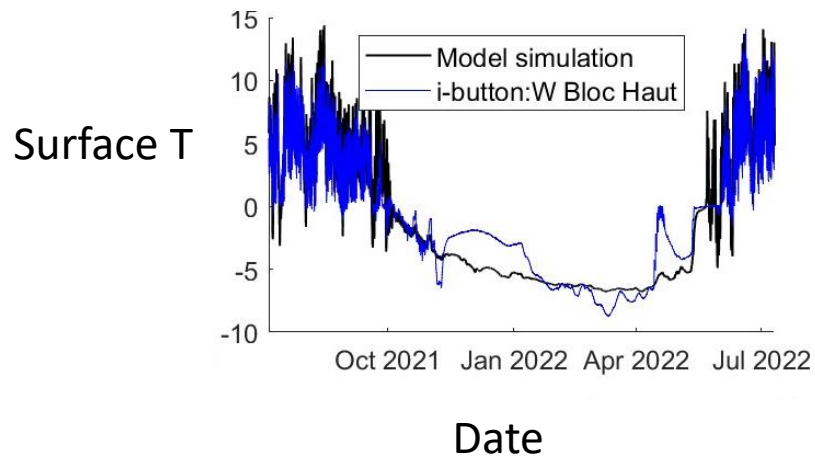
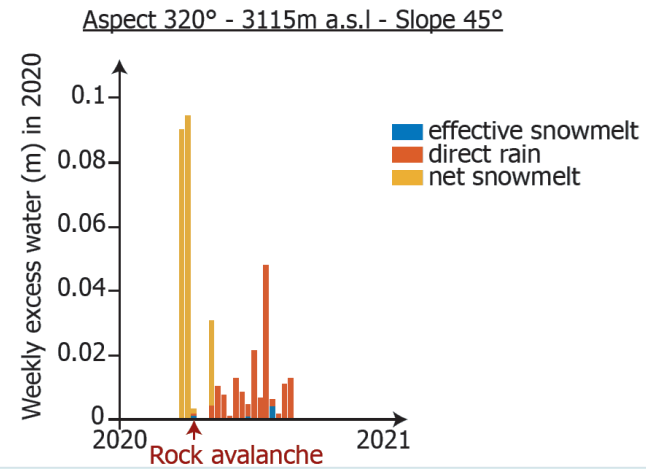
Rockfalls in the Mont Blanc massif 2007 – 2021 (courtesy of L. Ravanel)



Results – Surface temperatures

Go see poster #B39 for more – tomorrow

Vallon d'Etache rock fall, June 2020



Summary

- ❖ Our results provide new information about water balance at the surface of steep alpine rock slopes.
- ❖ The combined application of the S2M-SAFRAN dataset with the CryoGrid and CROCUS models is a powerful tool to study cryogenic and hydrologic processes in high alpine landscapes.
- ❖ Sublimation is systematically the main process of snow mass loss in our study site.
- ❖ Snowmelt occurs between late spring and late summer, and most of it may not reach the rock surface directly due to a formation of an impermeable ice layer at the base of the snowpack.
- ❖ The annual effective snowmelt that is available for infiltration is highly variable and ranges between 0.05 and 0.28 m in our study site.
- ❖ Snowmelt is the main source of water for infiltration at elevation >3600 m a.s.l.
- ❖ Below 3600 m, direct rainfall is becoming more dominant, and sublimation reduce. water availability increases rapidly – making this transition elevation highly sensitive to climate change, as snowmelt-dominated permafrost-affected slopes experience an abrupt increase in water input

*All models are wrong
but some are useful*



George E.P. Box

Field experiment – real-time monitoring of snowmelt using fluorescent dyes



Dye #1

Dye #2

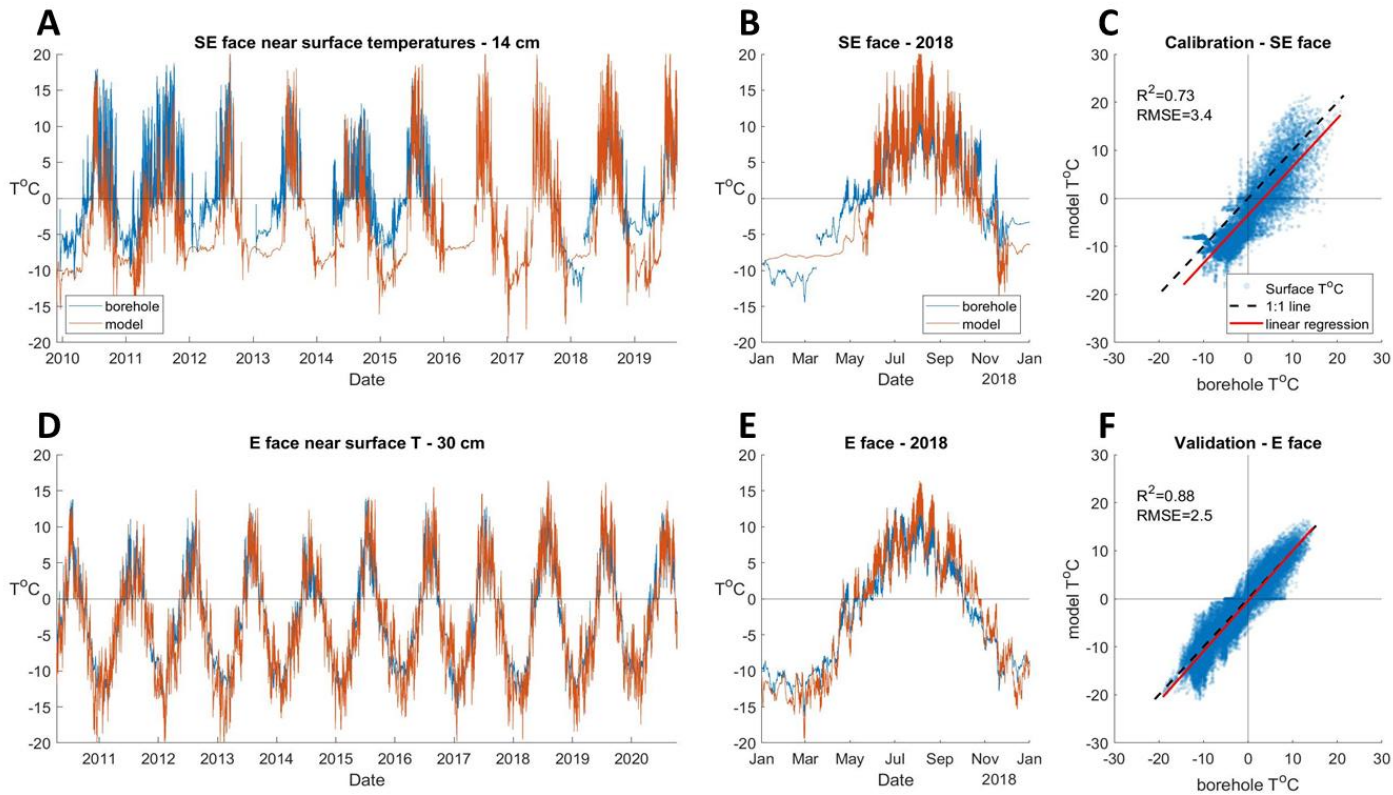


Figure 3 – Comparison of near surface T data from model and borehole measurements

A) Comparison of modelled near-surface T (orange) at depth 0.3 m, with borehole measurement from the SE face study site (blue).

B) Correlating modelled near-surface T with borehole measurements on the SE face after calibration of snow fraction factor (0.25) and maximum snow depth (0.8 m).

C) Validating the modelled near surface T at depth 0.14 m, with near-surface T data from a second borehole on the E face of AdM.



Model results – North vs. south

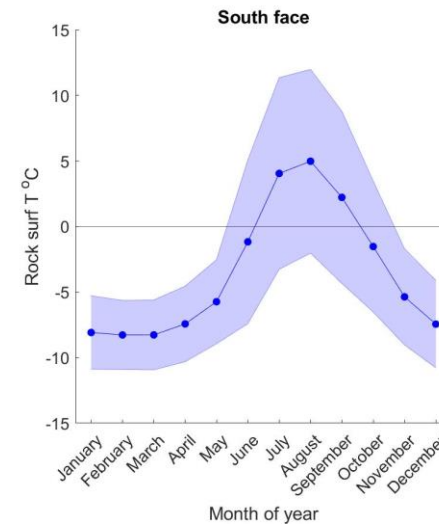
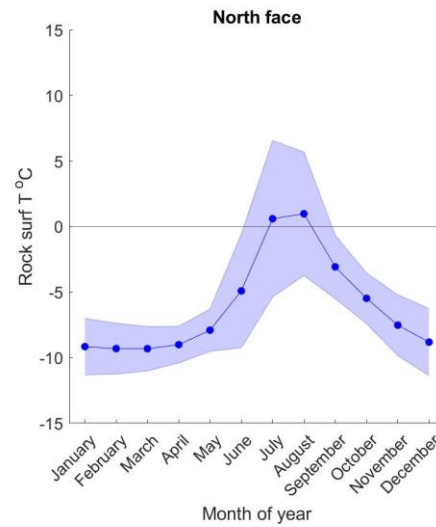
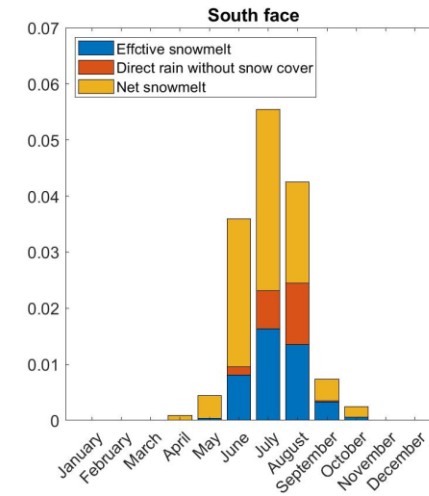
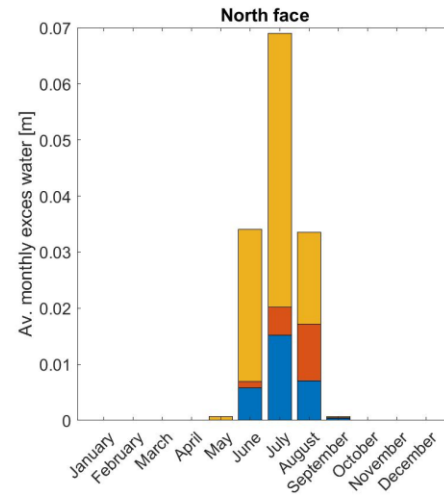


Figure 4 –Comparison of modelled snow accumulation with field measurements

A) Comparison of modeled snow depth (black line + light blue area) with snow depth measurement in proximal stations (See Fig. 1 for locations) in the Mont Blanc massif and its area: Aiguilles Rouges (blue) and Refuge du Requin (orange). Measurements were normalized to 0-0.8 m depth range for comparison.

B) Snow depth pole installed on the SE facing rock slope to monitor snow depth time series with a time lapse camera.

C) Comparing modeled snow depth, under different snow fraction values used in calibration, with measurements made in-situ using snow poles and time lapse camera. Note the optimum results with snow fraction value of 0.25 (25% accumulation).

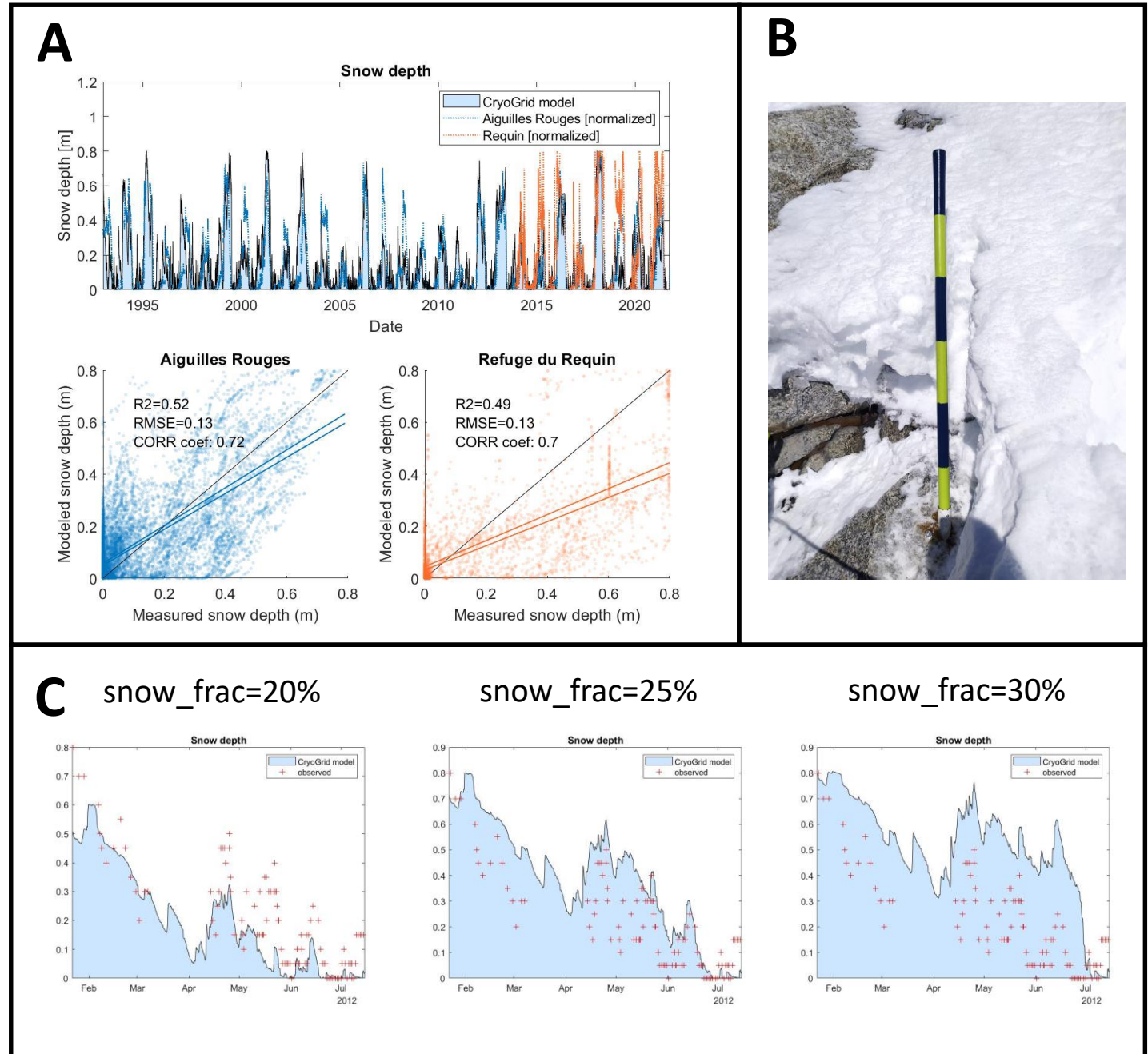
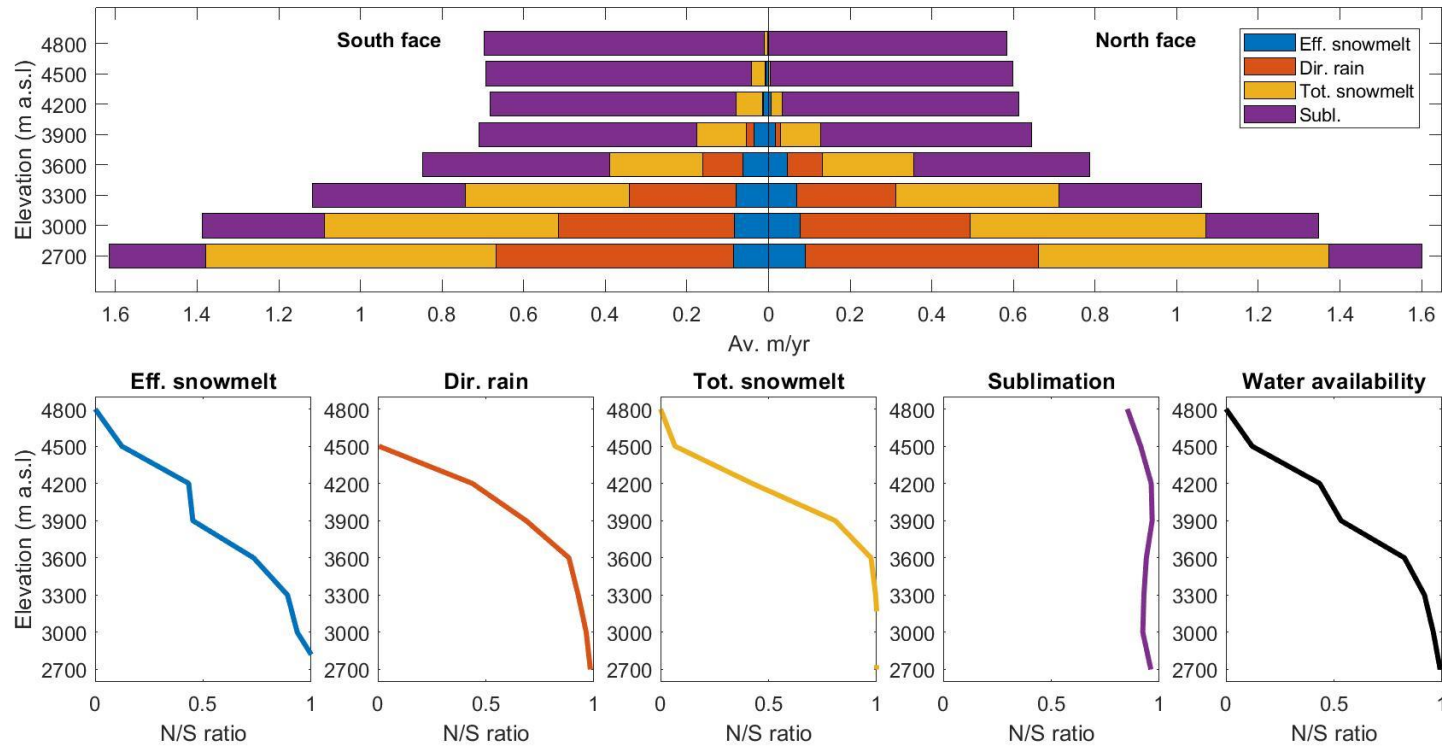


Figure 9 – North vs. south comparison of average monthly distribution of water fluxes at elevations of 2700 – 4800 m a.s.l.

Top - Comparison of average annual water fluxes, at elevations of 2700, 3000, 3300, 3600, 3900, 4200, 4500, 4800 m a.s.l. on north (left) and south (right) facing rock slopes.

Bottom – The ratio between north to south of each water of the water fluxes described above, in each of the modelled elevations. A value of 1 represents equal flux on both aspects and values decreasing toward 0 represent larger ratio between S to N face (for example, a value of 0.5 corresponds to $\times 2$ higher flux on the S face). The bottom right image shows the flux of net water availability at the rock surface, that is available for infiltration (effective snowmelt + direct rain). Note that at elevations < 3000 m a.s.l fluxes are similar on both aspects and the ratio decreases at higher elevations but the water fluxes magnitudes decrease.



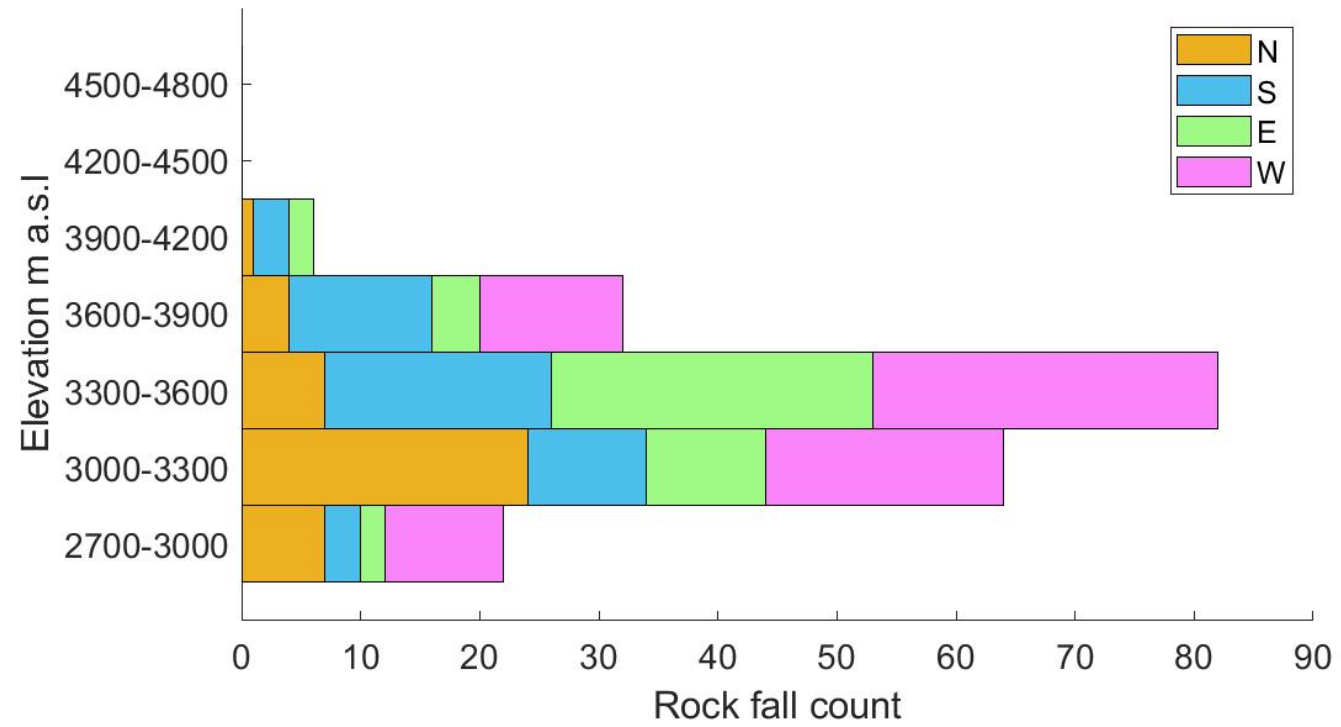


Figure 11 – Slope distribution and hypsometric curve

Spatial analysis of a digital elevation model with a resolution 0.2 m cell size and an area of 100 km² around the AdM. A) Average slope at elevation bins on 300 m between 1200-4800 m a.s.l. Analysis was made on pixel with slope angle >40° which was shown to be the threshold value for the slope influence on snow accumulation. B) Elevation distribution in the Mont Blanc massif.

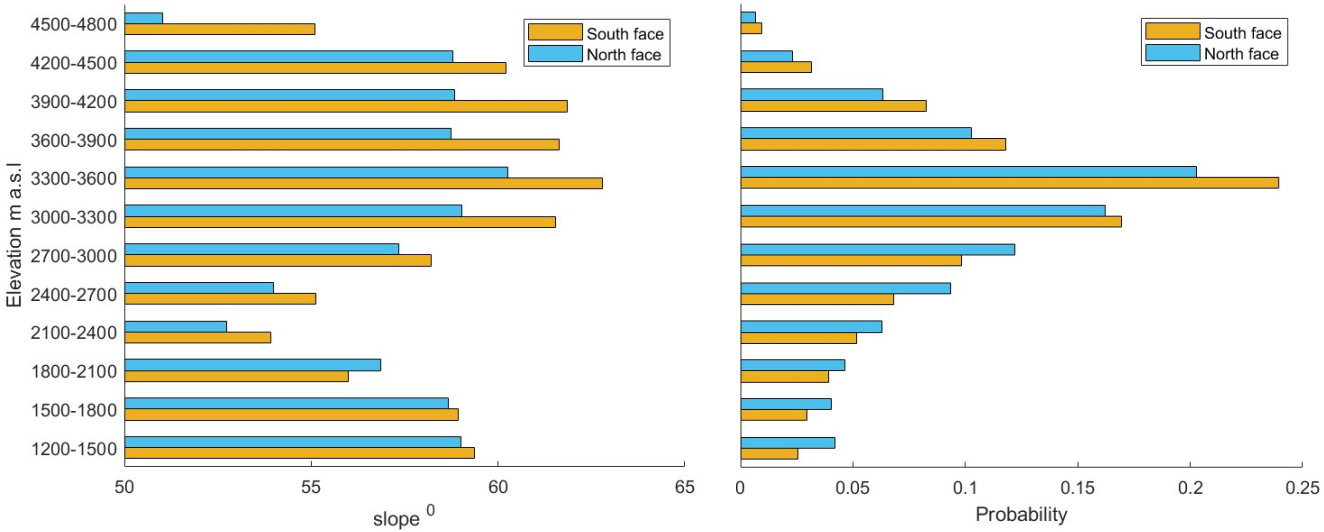


Figure S1 – Ice crust

Field photos showing ice crust at the bottom of the snowpack exposed during fieldwork at the Aiguille du Midi SE face. Photos were taken on 26th January 2022.

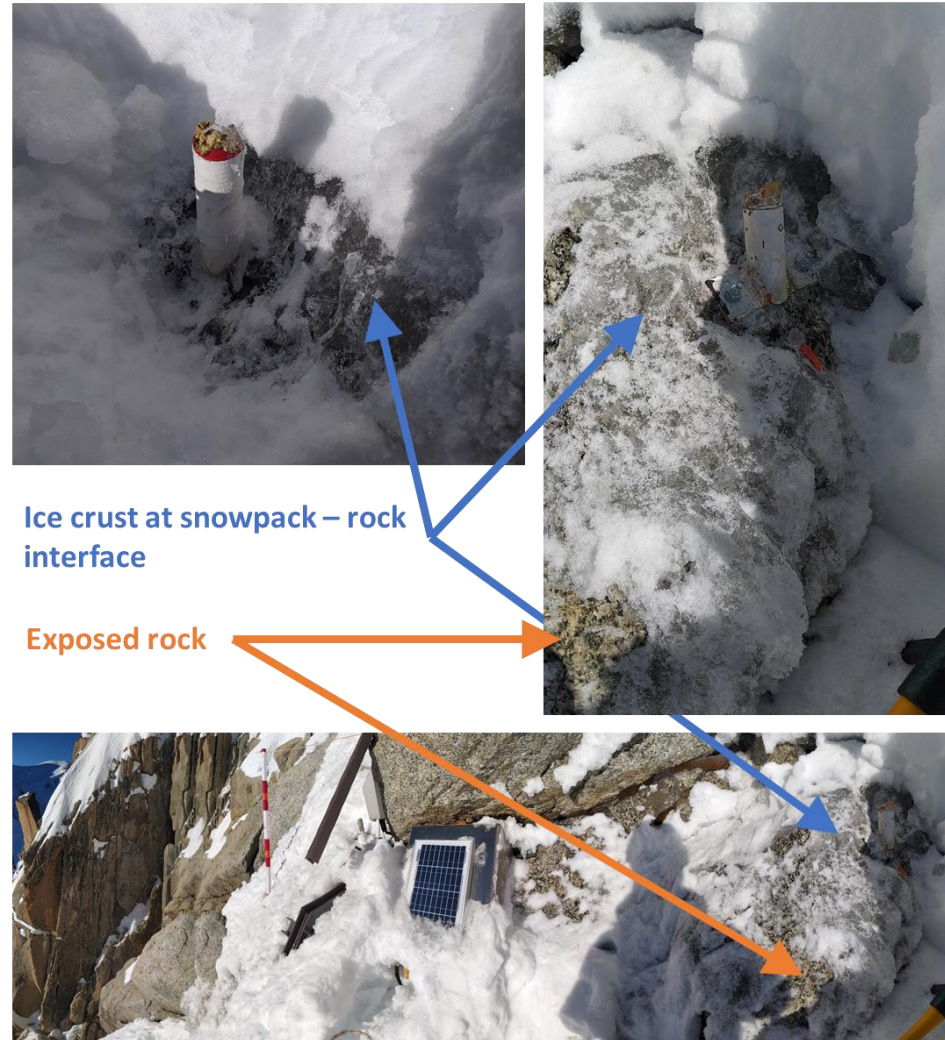


Figure S6 – Example of time-lapse images of a snow depth pole installed on the east face. Pole height is 1m with black/white scales of 10 cm.

