



Rock Slope Stability 2021



Chutes de Blocs
Risques Rocheux
Ouvrages de Protection



Modeling rockwall permafrost to understand periglacial rock slope failures

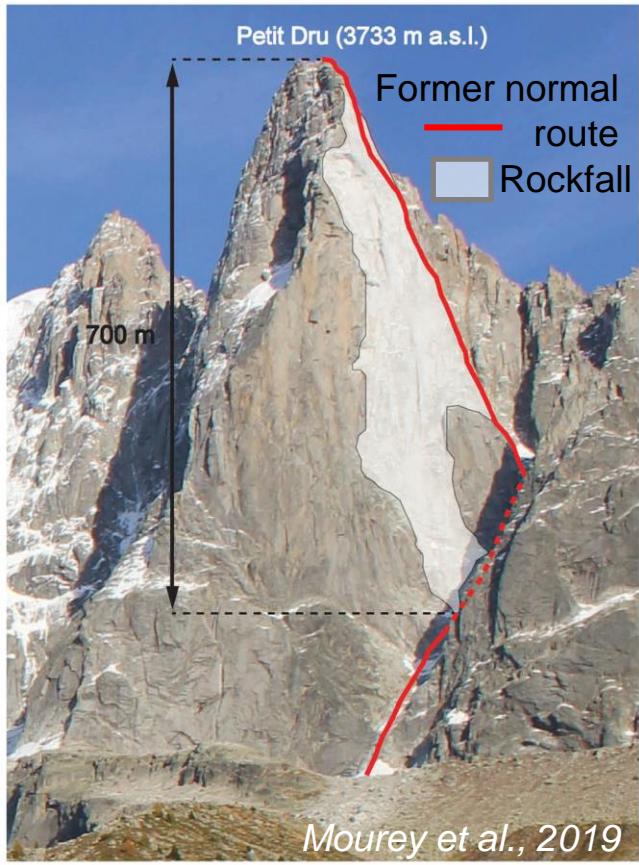
F. Magnin, P. Deline, P-A. Duvillard, J-Y. Josnin, A. Legay, L. Ravanel

Symposium Rock Slope Stability 2021

November 17 & 18, 2021



Change in mountain practices and professional guiding activities

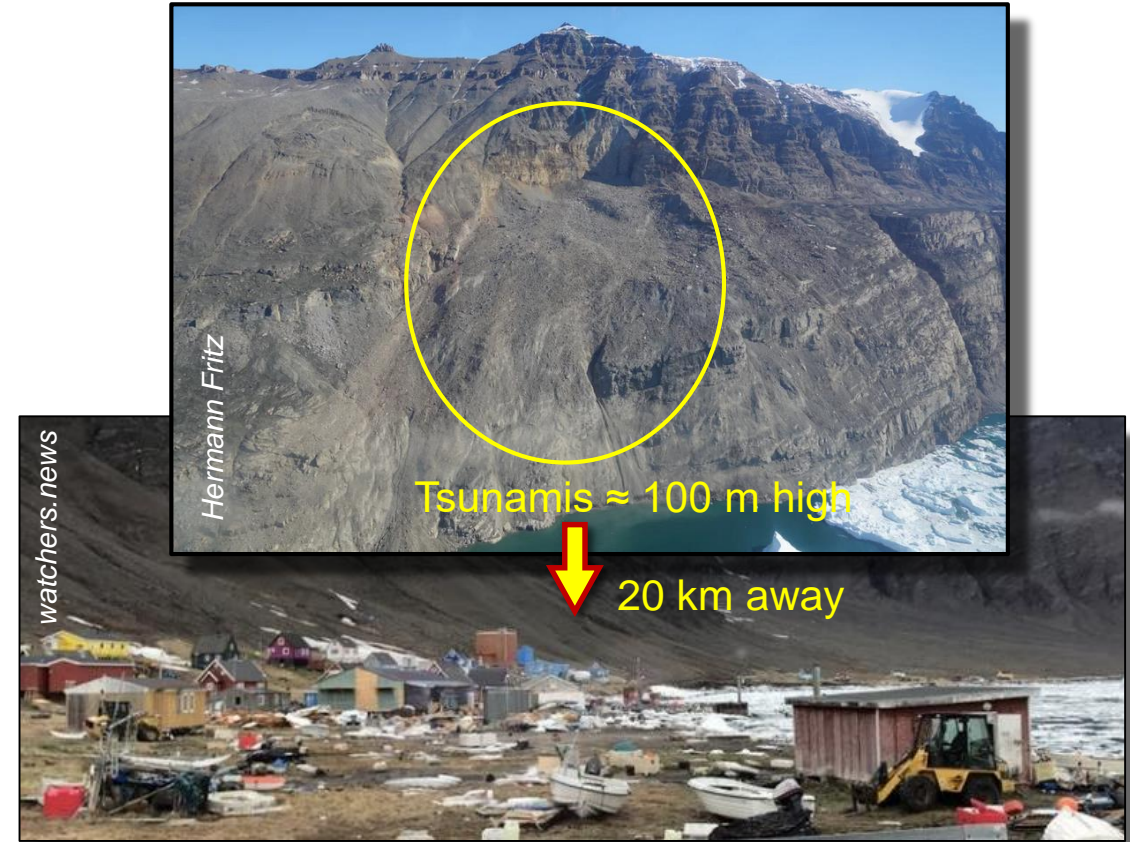


Piz Cengalo rock avalanche Switzerland- August 2017



Chain reaction processes with far-reaching impacts

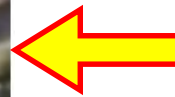
Rock avalanche in Karrat Fjord - Greenland – June 2017

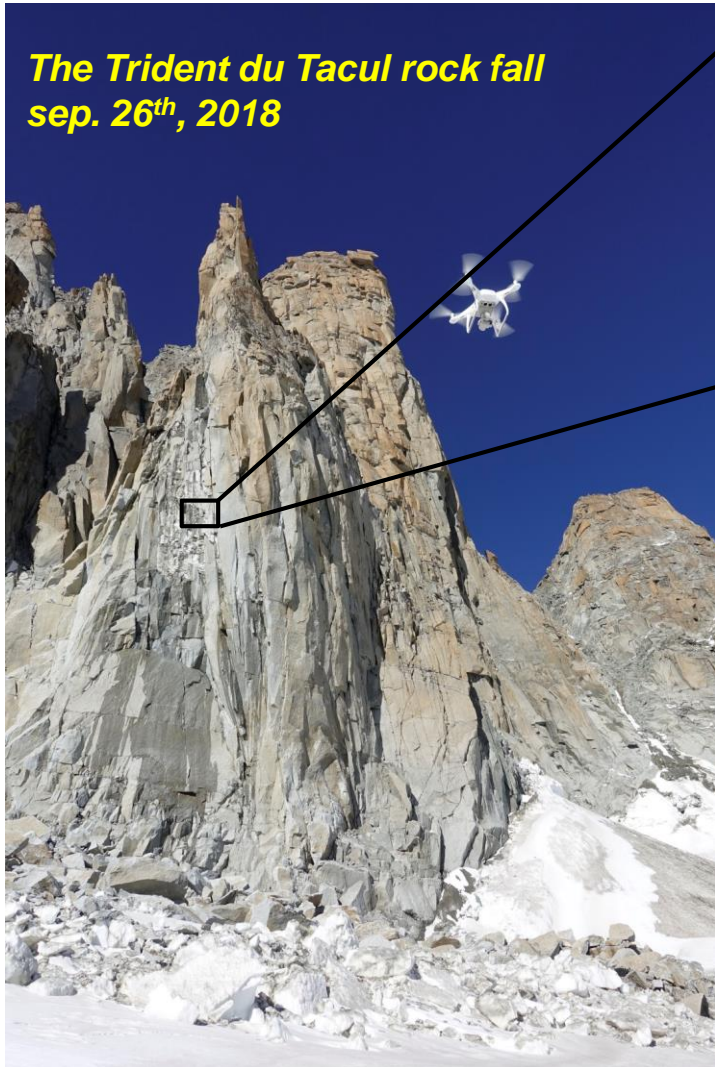


Will such catastrophic failures increase in the coming years and decades ?

→ We need to understand the triggering mechanisms of these failures

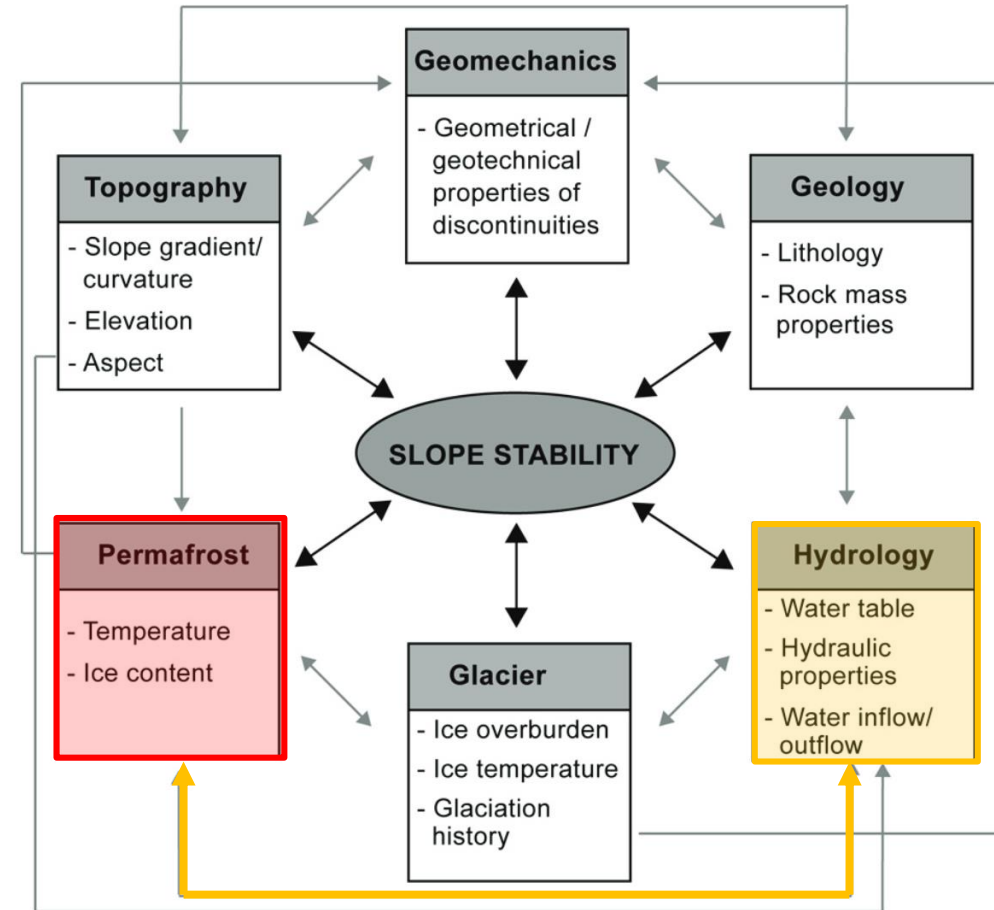
**Chamoli rock-ice avalanche—
February 2021**





Permafrost degradation is the main factor responsible for this increase in periglacial rock slope failures, either because of:

- **decrease in shear resistance** of ice-filled fractures
- **critical hydrostatic pressures** at ice-sealed fractures and rock mass



Fischer and Huggel, 2008

- 1. Systematic inventory of rockfalls in the Mont Blanc massif since 2007
 - has shown an evident relationship between hot periods (decade or season) and rockfalls frequency

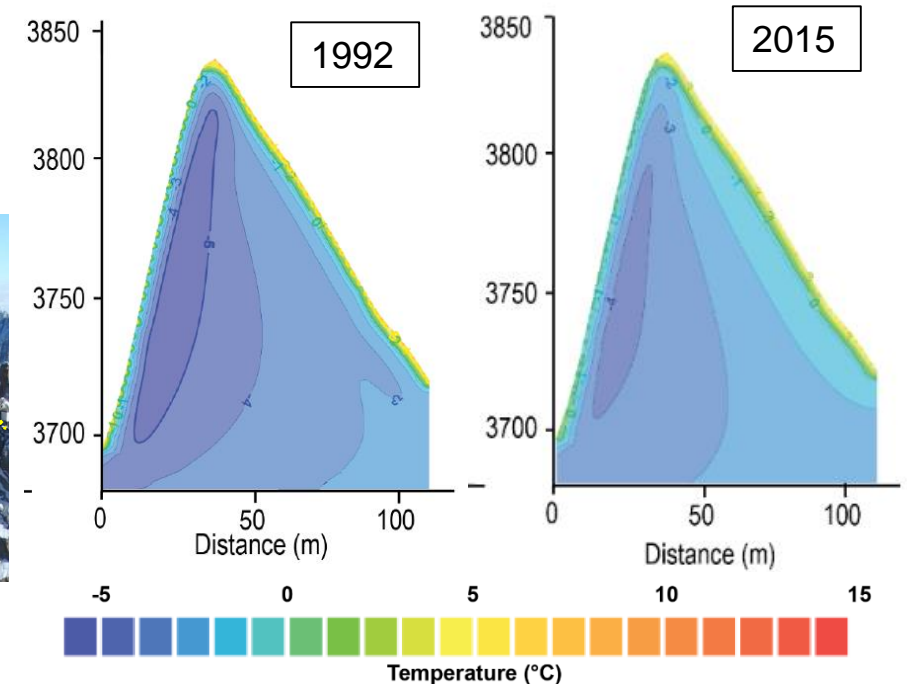
→ Is there a statistical relationship between rockwall temperature and rockfall occurrence ?

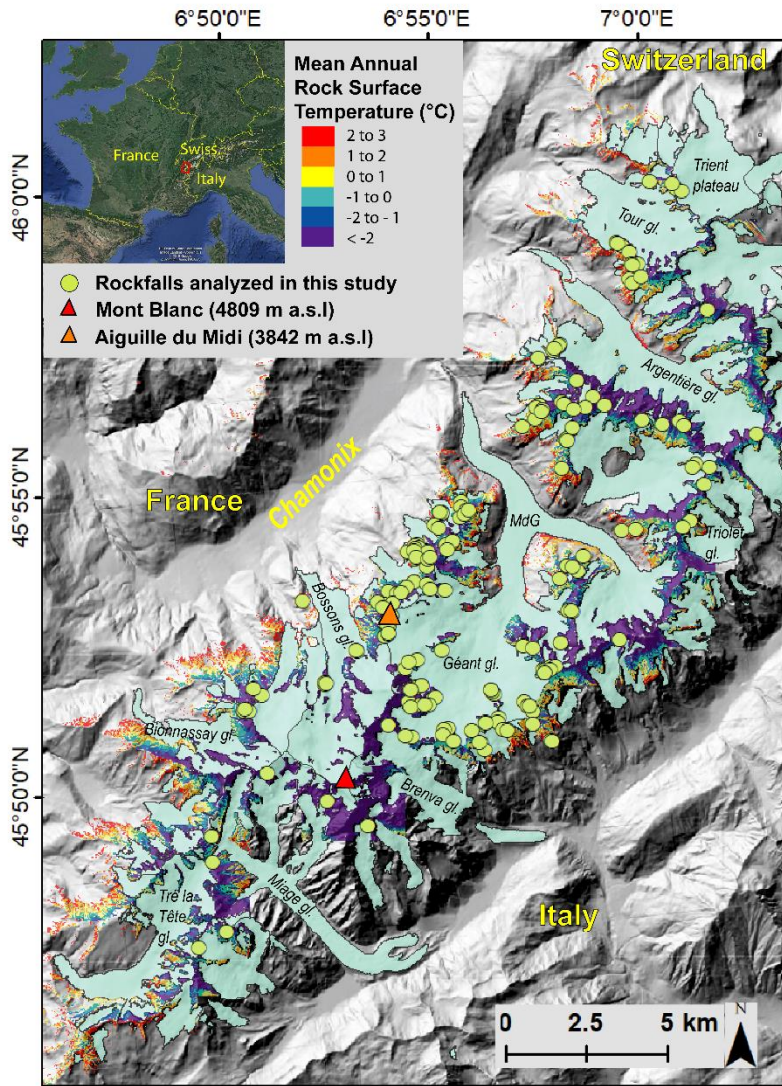


- 2. Transient thermal models to assess permafrost depth and evolution
 - Rockwall permafrost has degraded over the past 3 decades

→ What is the role of hydrological processes in permafrost dynamics ?

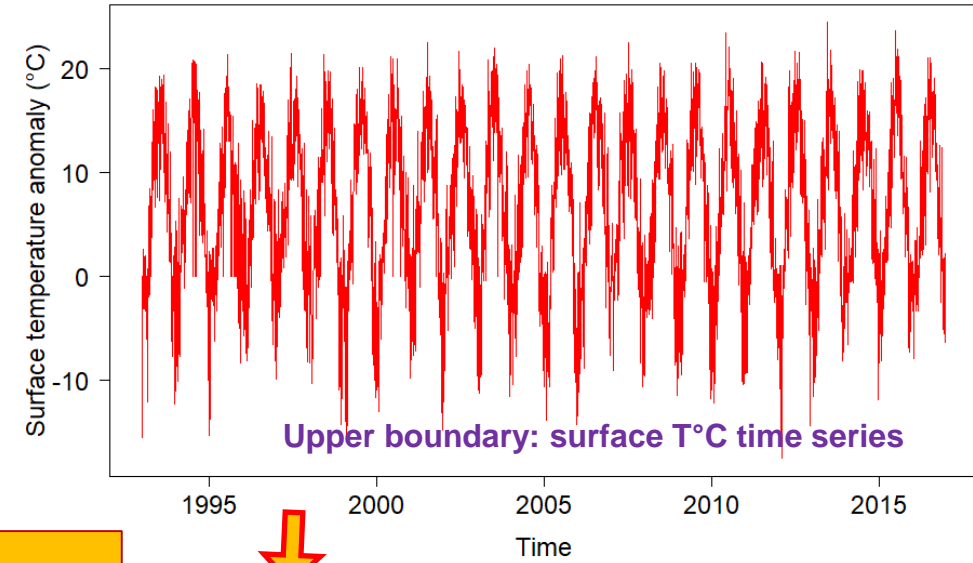
Aiguille du Midi
3842 m a.s.l





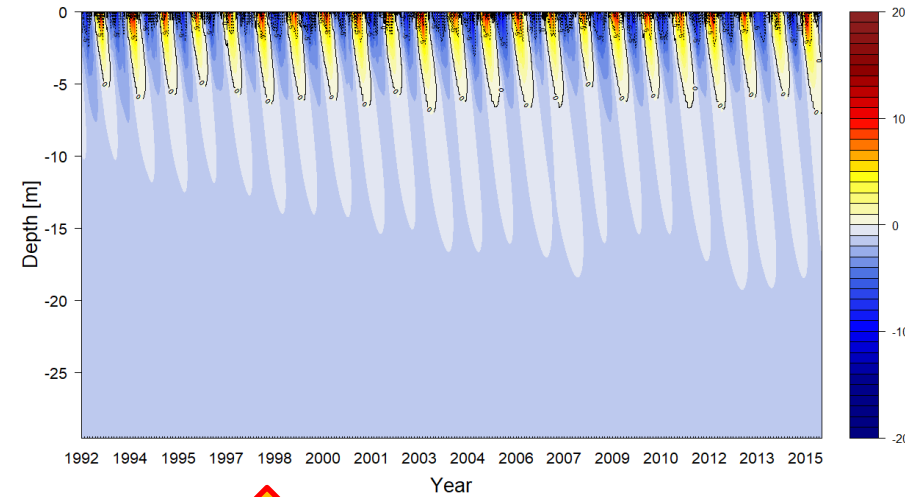
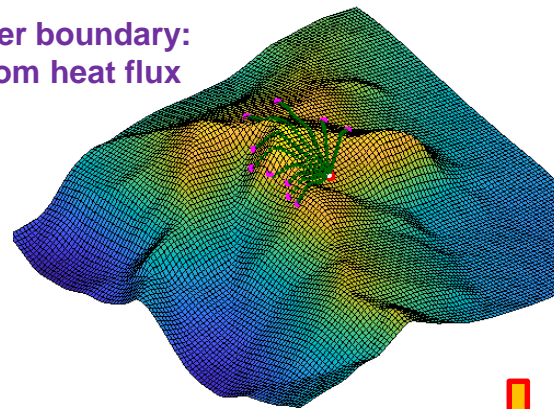
Data and modelling approach

- 209 rockfall events
- Coordinates, date of occurrence, and detachment depths are known
- The Mean Annual Rock Surface Temperature for the period 1961-1990 is extracted from the map



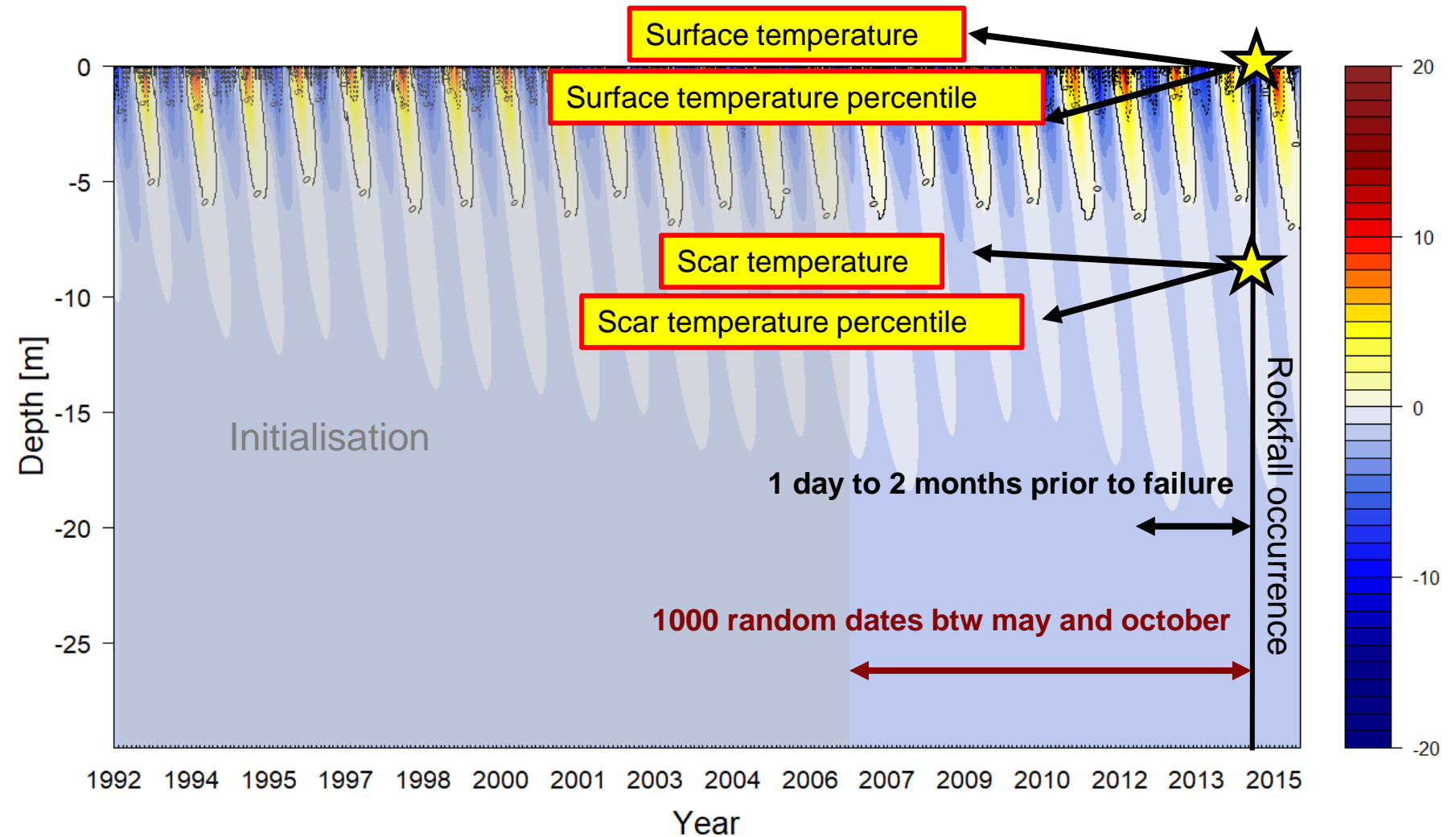
1D transient thermal model

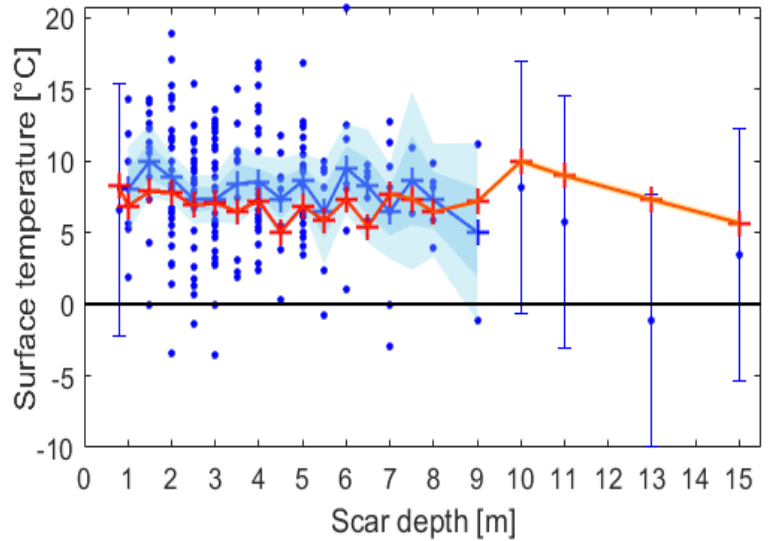
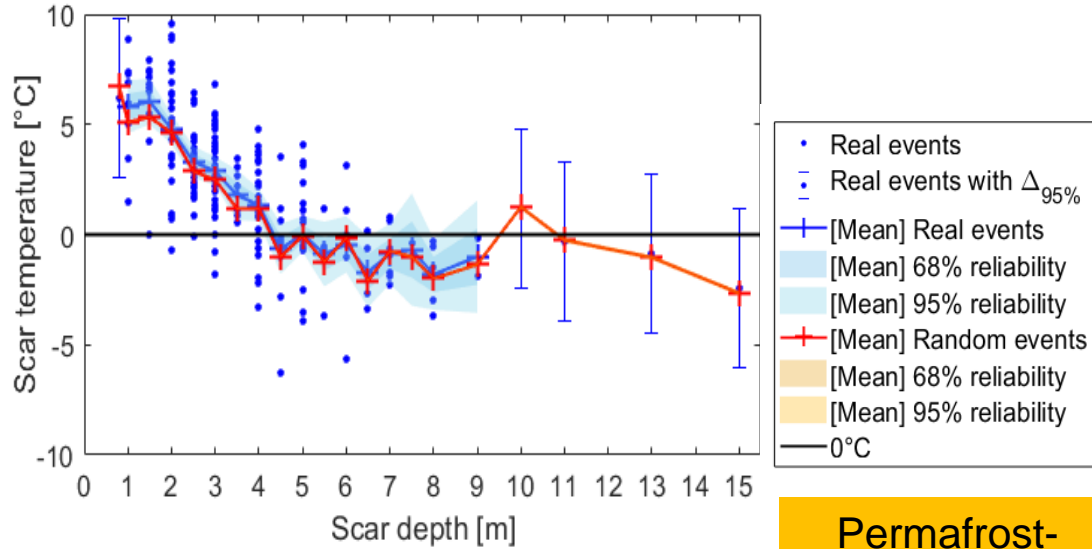
Lower boundary:
bottom heat flux



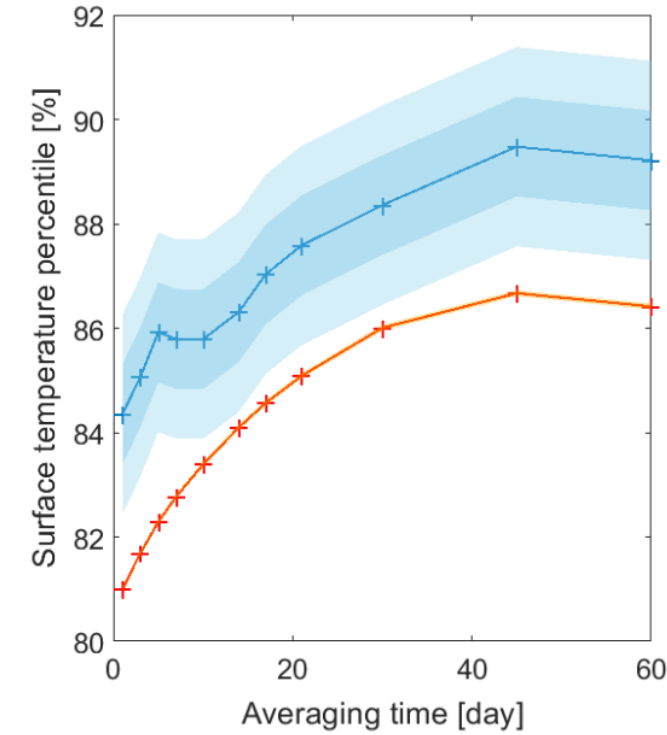
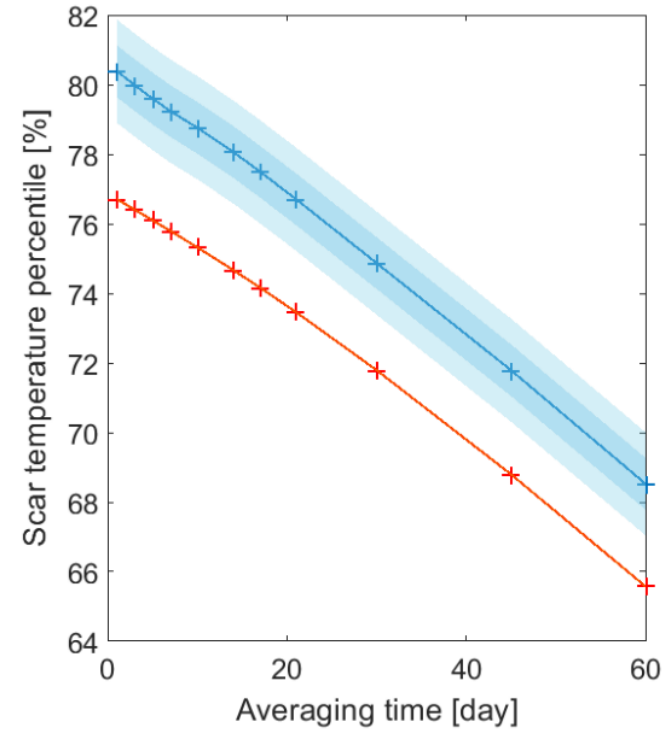
Results analysis

- **4 temperature variables** are considered to analyze temperature conditions and dynamics prior to failure
- **Various temporalities prior to failure ranging from the day of occurrence to 2 months before** are considered
- **1000 random events at each rock fall location** (209 000 in total) drawn according to the statistics of rockfall timing (distribution over the year)
- **Uncertainties** for the initial MARST, RST time series and model parameters **are quantified.**





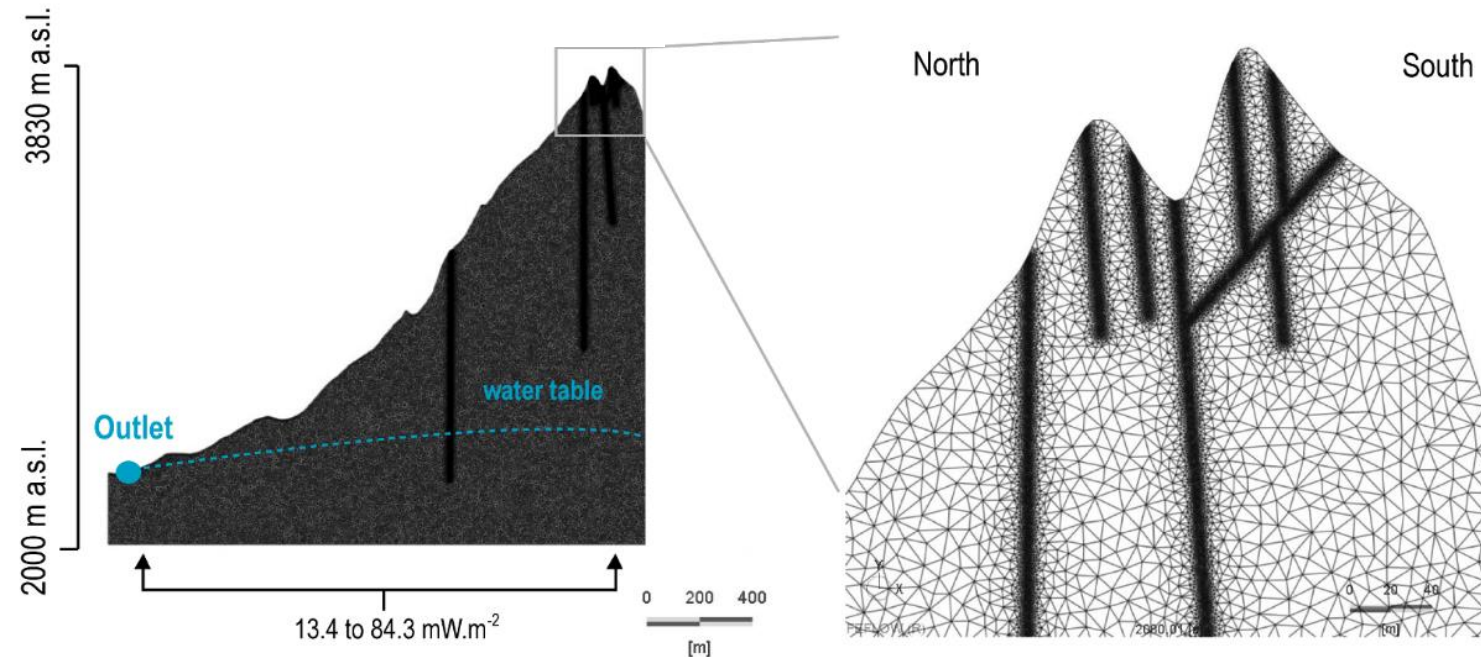
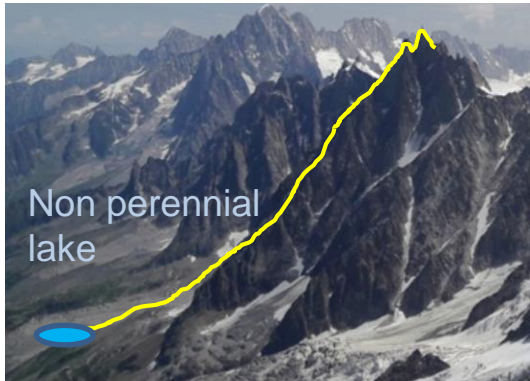
Permafrost-related rockfalls may generally concern events > 6 m and most events < 4 m depth are not related to permafrost



- Extraordinary high temperature lasting for several weeks are prone to rockfall occurrence
 - Rockfalls are a direct reaction to extraordinary high temperature at depth.

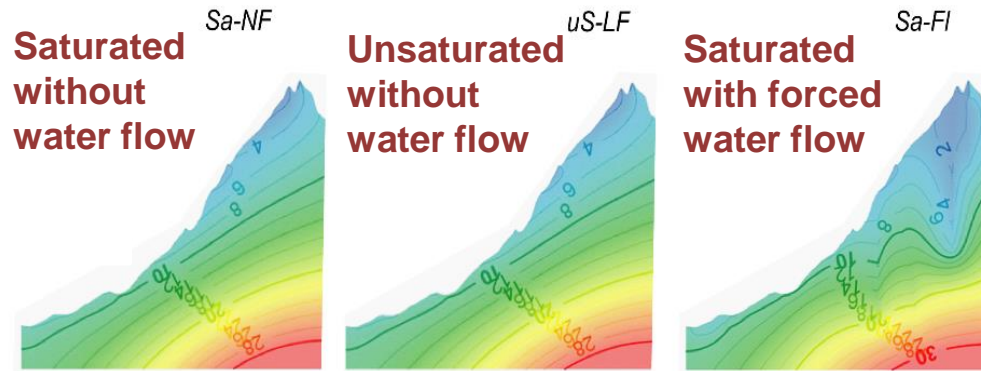
Model set up and modeling approach

- Model domain according to hydrogeological settings for non-frozen conditions (water table and fractures as preferential flow paths)
- Fully coupled thermal and hydrological simulations with Feflow®
- Darcy law plugged into the continuity equation



Accepted in *Journal of Geophysical Research: Earth Surface*

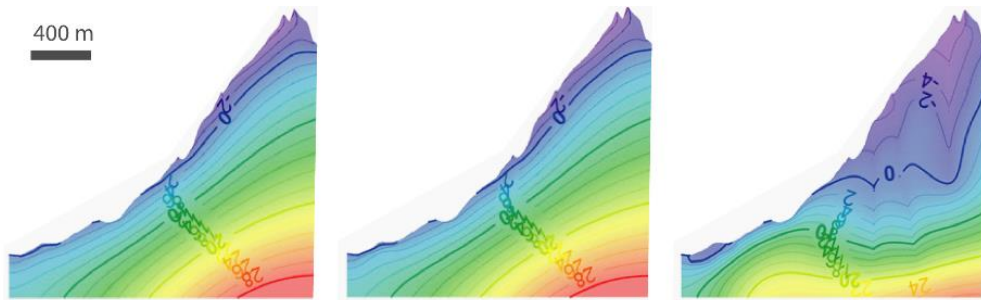
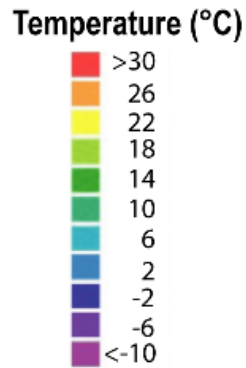
After initialization
(thawed conditions)



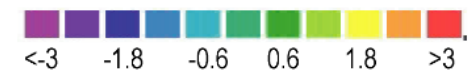
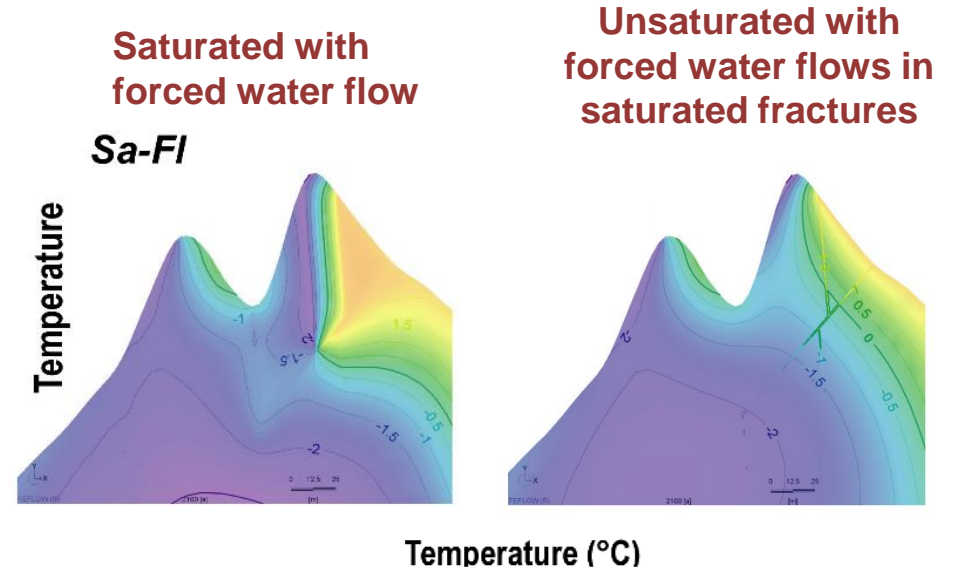
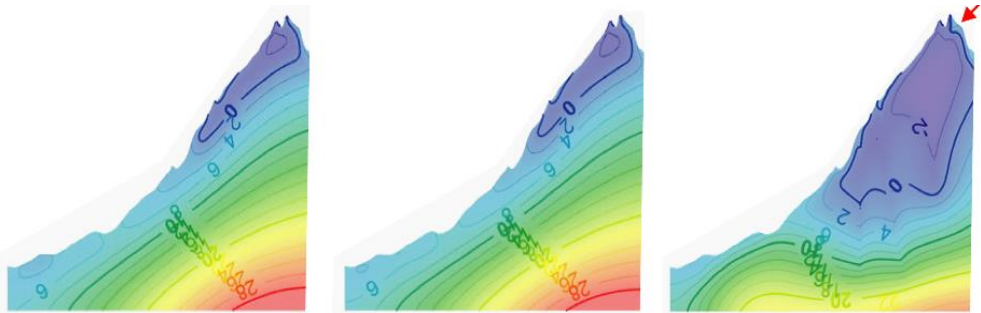
Water flows into rockwall fractures strongly affect the freezing and thawing patterns:

- Temperature gradients are more complex
- Thawing is enhanced in saturated conditions

During steady freezing



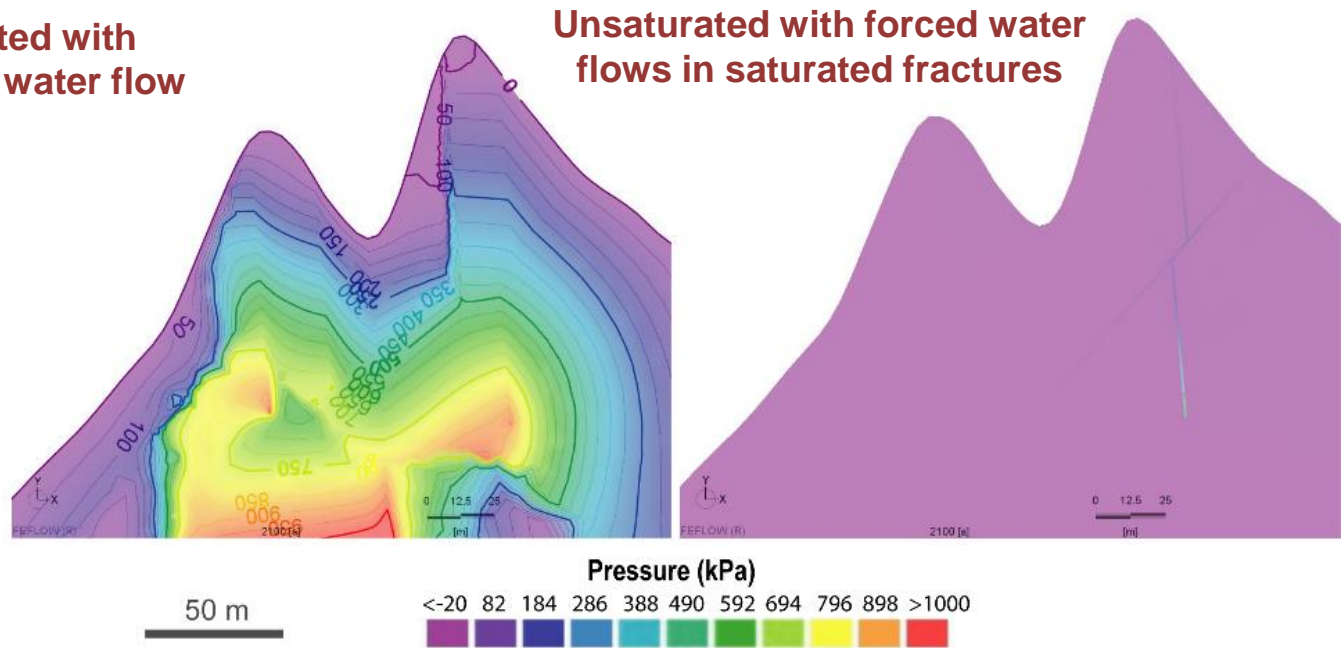
During steady thawing



There is a need for a better understanding of periglacial rockwall destabilization processes in order to support Alpine and Arctic communities in their adaptation strategy to a changing cryosphere

→ We need to understand the triggering mechanisms of these failures

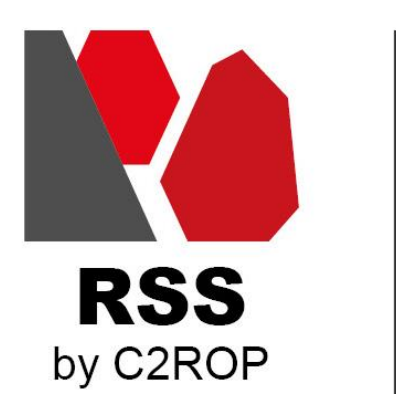
- 1. There a statistical relationship rockwall temperature and rockfall occurrence
 - A first step towards the determination of rockfall susceptibility index according to weather forecast
- 2. Water flows may enhance permafrost thawing and may lead to critical hydrostatic pressures values
 - A first step towards fully coupled thermo-hydro-mechanical models to analyze frozen rockwall destabilization



Pressure > 100 kPa may be critical and trigger rockfalls (Stoll et al., 2020)

Accepted in
Journal of
Geophysical
Research:
Earth Surface

Stoll, V., Scandroglio, R., Krautblatter, M., 2020. **Modelling rock walls destabilization caused by hydrostatic pressure in frozen/unfrozen bedrock (Hochvogel & Zugspitze, Germany).** Presented at the EGU General Assembly, Vienna, Austria. <https://doi.org/doi.org/10.5194/egusphere-egu2020-14338>



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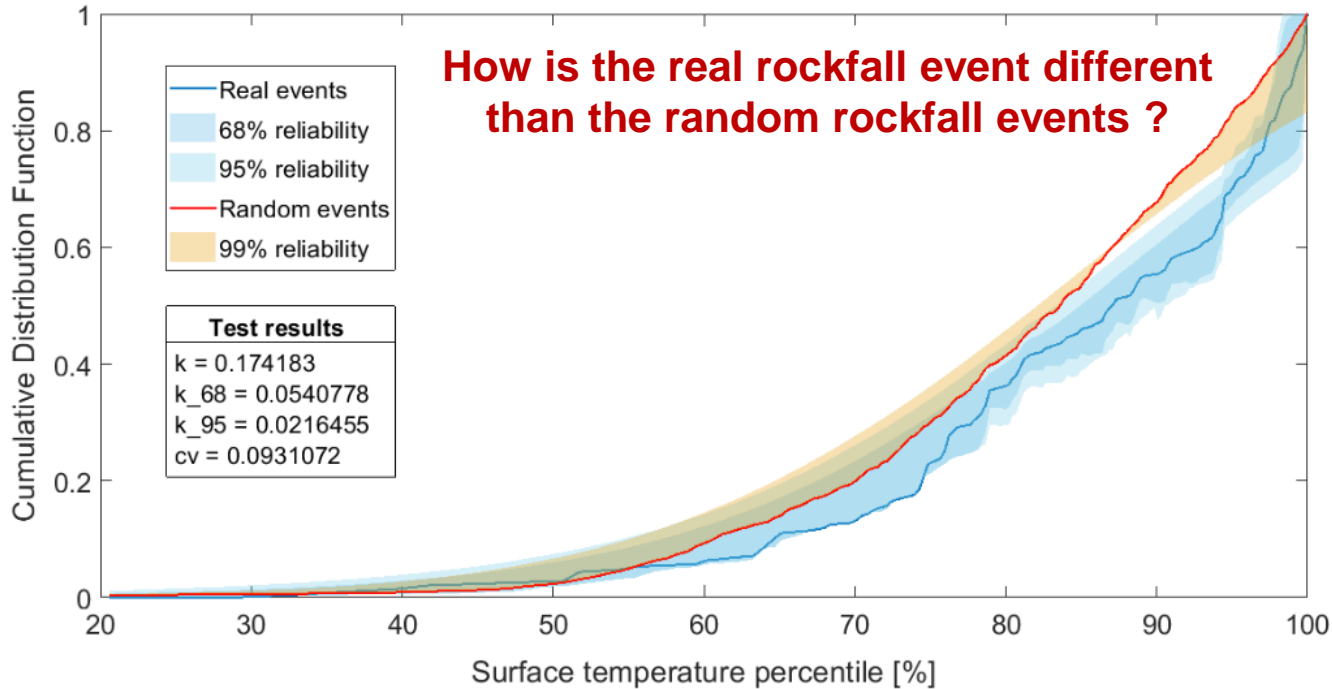
Merci pour votre attention
Thank you for your attention

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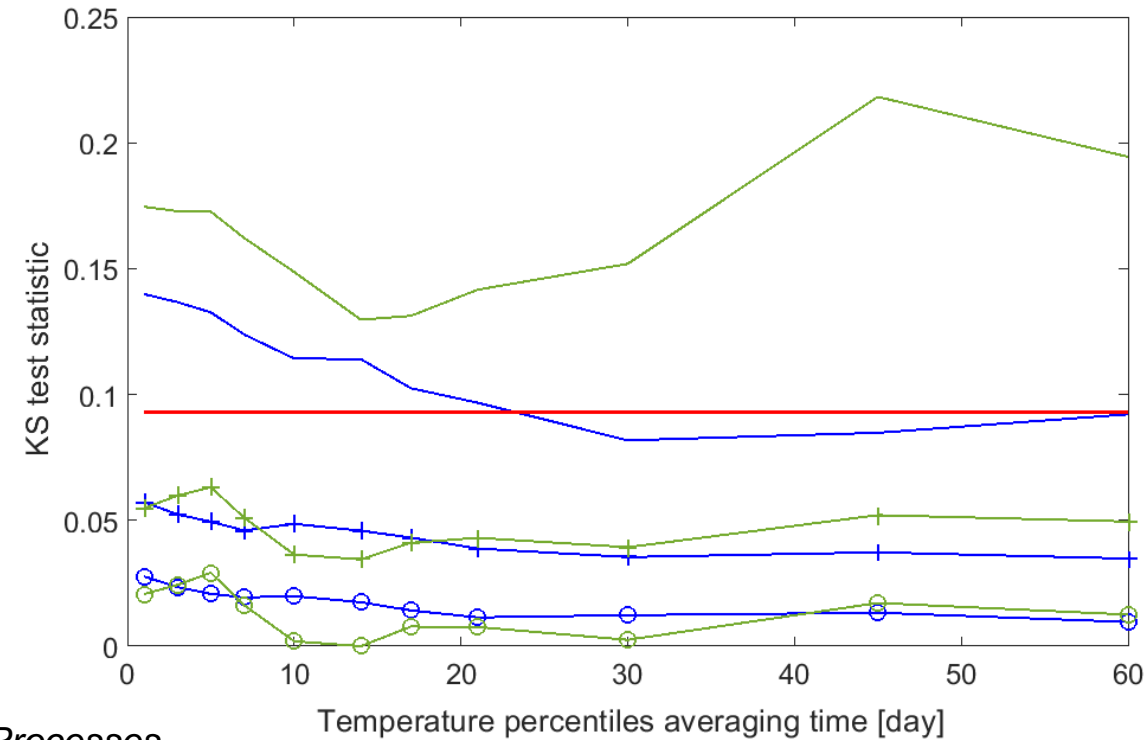


- Results of the real events simulations are compared to those of the random events in a Kolmogorov-Smirnov test (KS) to determine their statistical significance



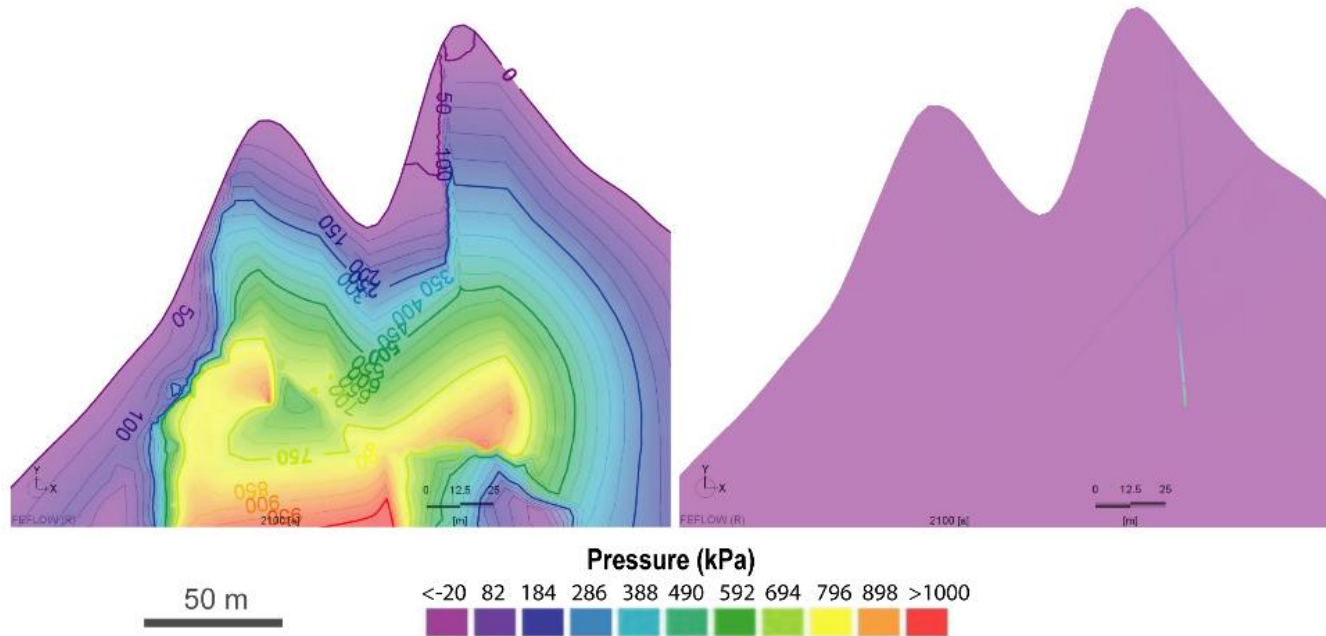
➔ Such statistics could support the development of a rockfall susceptibility index using weather forecast

- Hot periods lasting at least 1.5 month combined with 1-5 days hot spell are particularly prone to rockfalls.
- Rockfalls are a direct reaction to extraordinary high temperature at depth.



Saturated with forced water flow

Unsaturated with forced water flows in saturated fractures



Hydrostatic pressures have complex patterns under fully saturated conditions

Critical values of 0.1 Mpa as determined by Stoll et al. 2020* may be easily reached in thawing fractures and surrounding rock mass

→ Such data could be integrated into discrete element models describing the mechanical behaviour of frozen rockwalls to better assess hydrothermal conditions prone to rockwall failures (e.g. Stoll et al. 2020)

Accepted in *Journal of Geophysical Research: Earth Surface*

*Stoll, V., Scandroglio, R., Krautblatter, M., 2020. **Modelling rock walls destabilization caused by hydrostatic pressure in frozen/unfrozen bedrock (Hochvogel & Zugspitze, Germany). Presented at the EGU General Assembly, Vienna, Austria.** <https://doi.org/doi.org/10.5194/egusphere-egu2020-14338>

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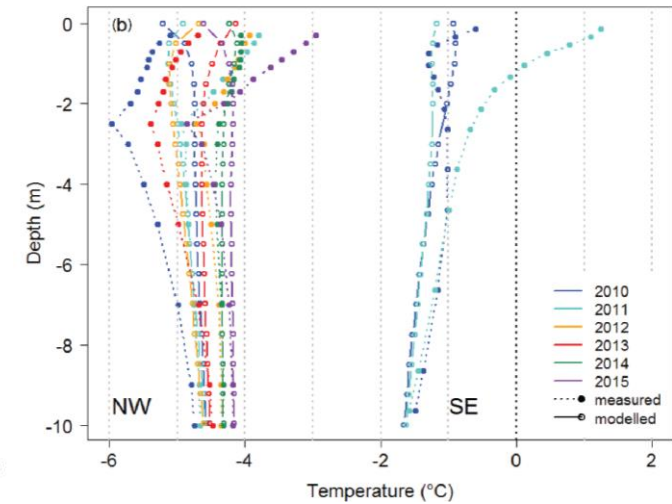
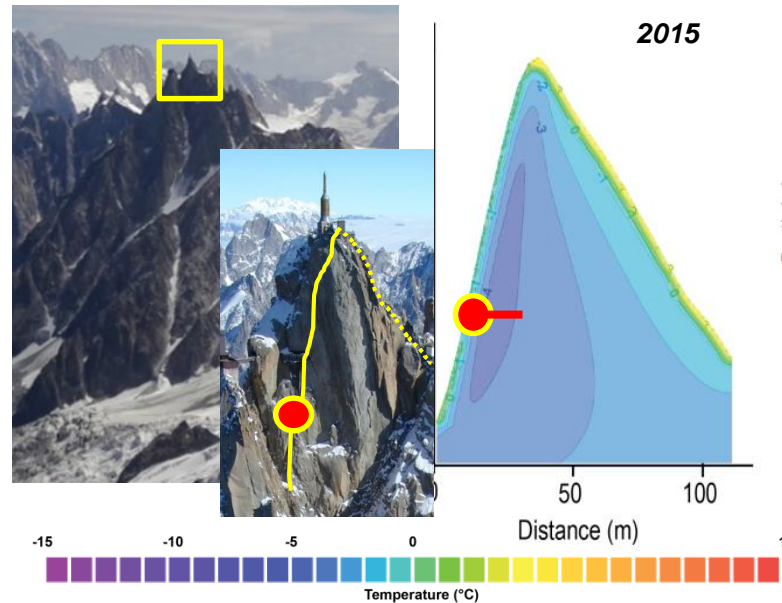


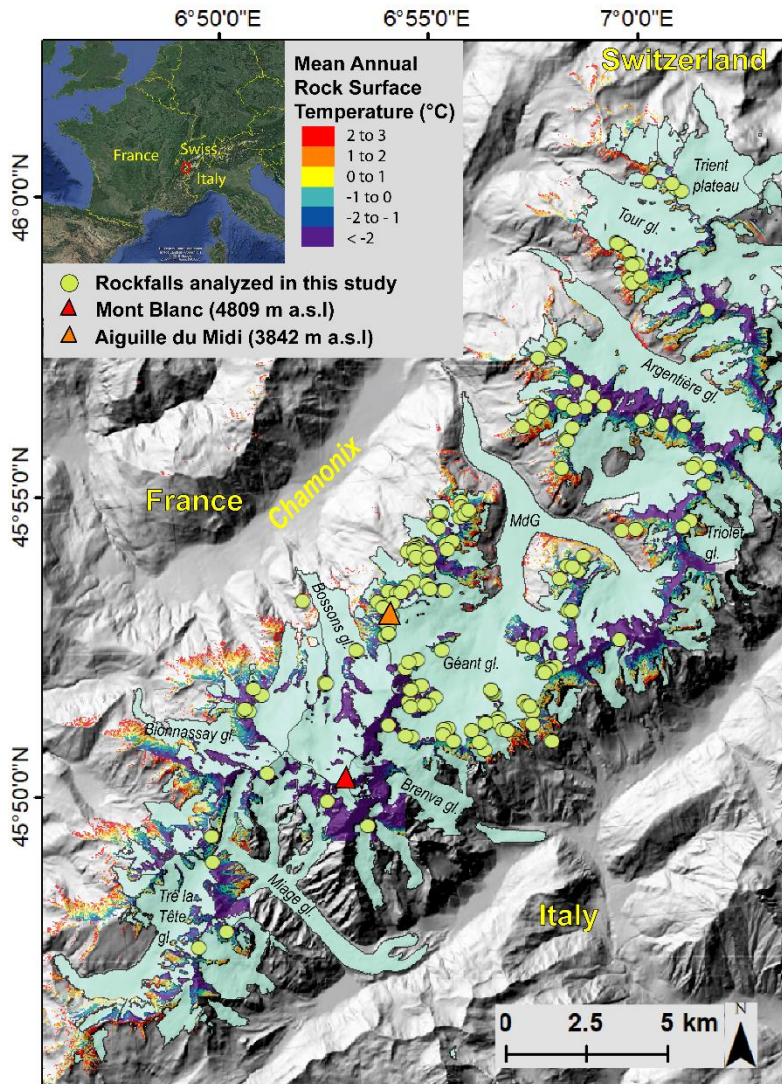
2. Transient thermal models compared to borehole temperature data

- Rockwall permafrost has degraded over the past 3 decades
- Rockwall temperature evolution is accurately simulated at depth > 8 m

→ What is the role of hydrological processes in permafrost dynamics ?

Aiguille du Midi – 3842 m a.s.l



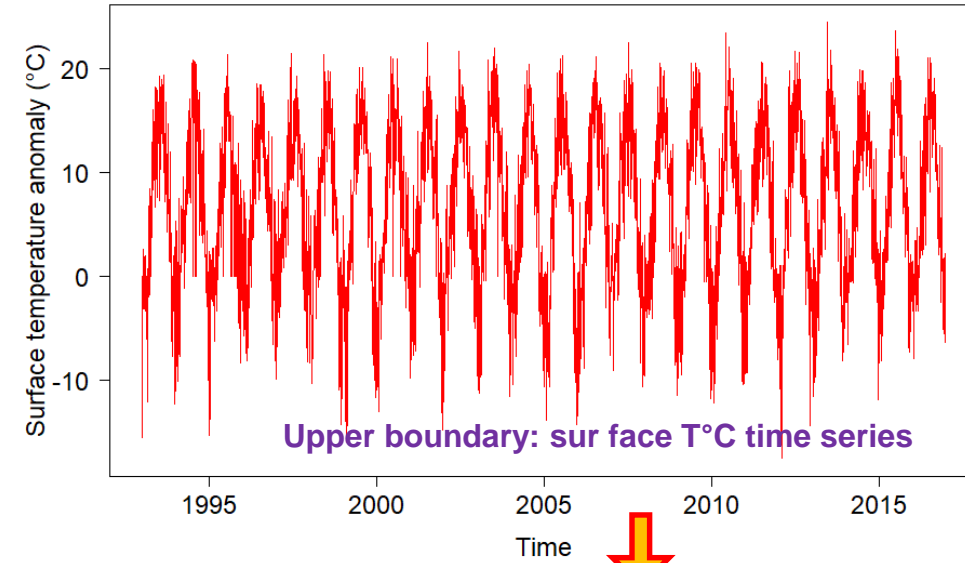


Data

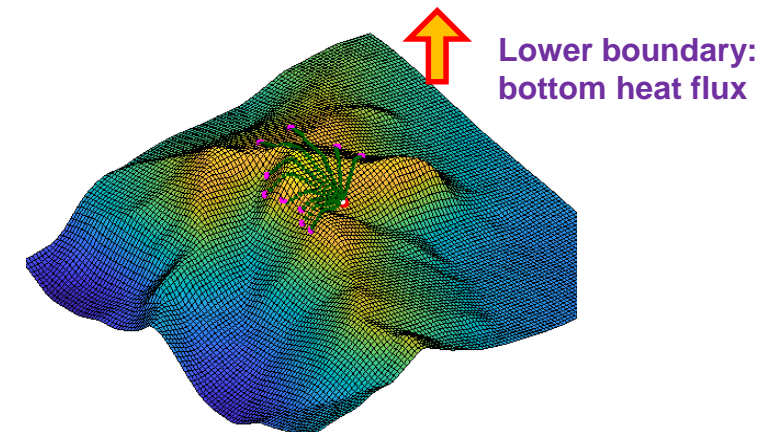
- **209 rockfall events** (100 to 60 000 m³) selected from an inventory collected in the Mont Blanc massif btw 2007- 2015
- Coordinates, date of occurrence, and detachment depths are known
- The Mean Annual Rock Surface Temperature for the period 1961- 1990 is extracted from the map

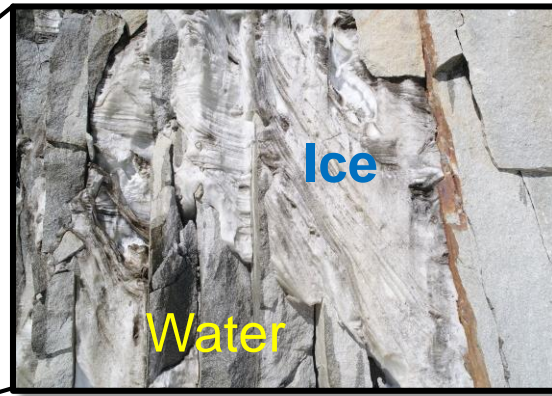
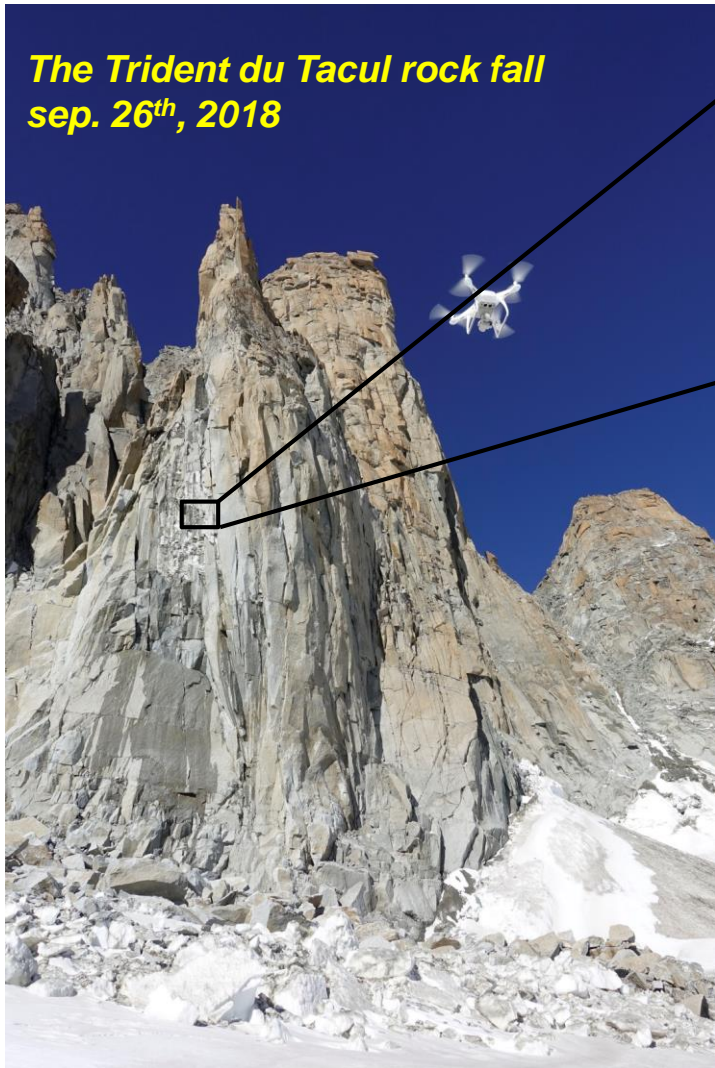
Modeling approach

- Temperature profiles are simulated at a daily time step for each event from the surface to the depth of failure, from 1993 to 2016 with the **CRYOGRID2 transient diffusive thermal model** (Westermann et al., 2013).
- **Rock surface temperature (RST) time series are created** from air temperature anomaly applied to the initial MARST to force transient thermal modeling.
- **A correction heat flux** is calculated to account for possible lateral heat fluxes from surrounding rock faces.

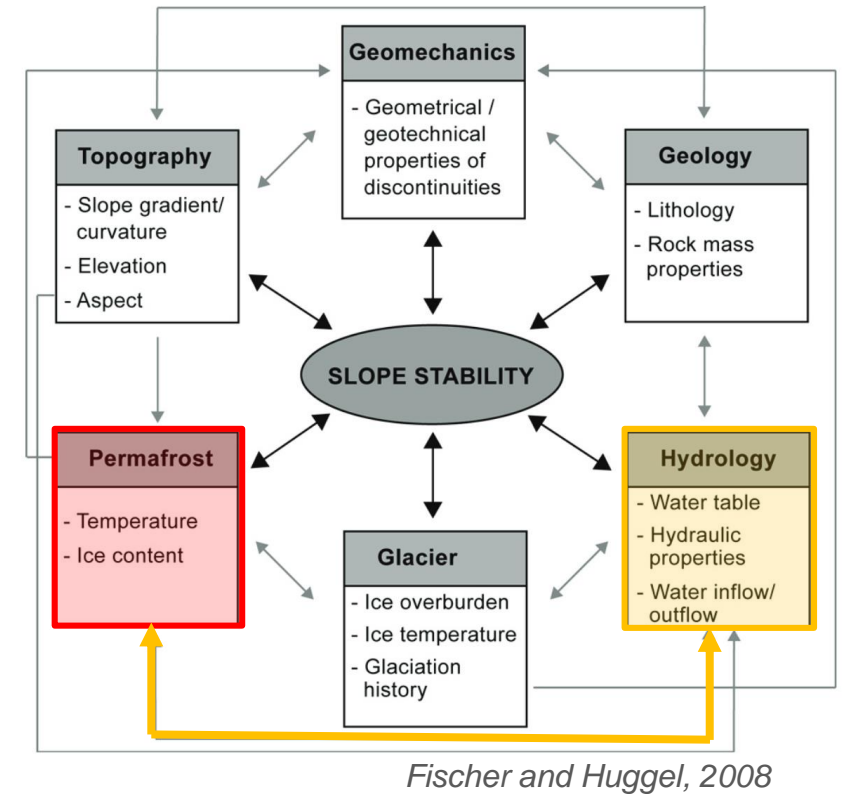
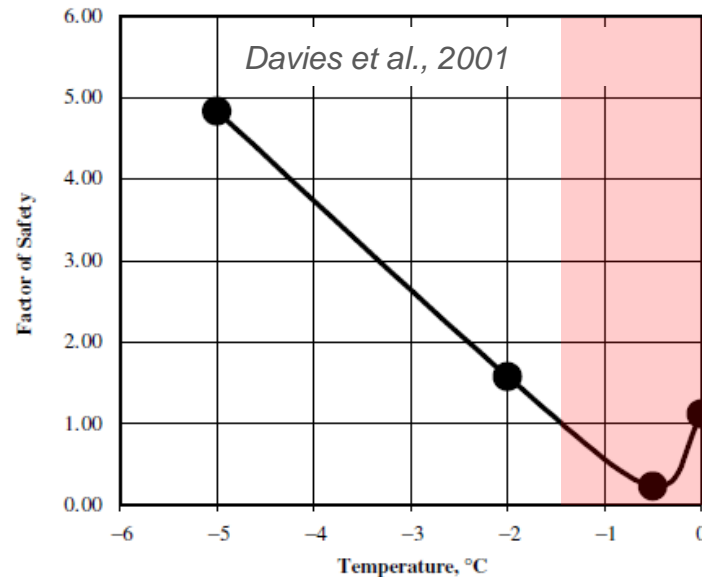


1D transient thermal model





Shear resistance of an ice-filled joint between bedrock compartments



Rockfalls may be triggered by:

- A decrease of shear resistance of ice-filled fractures, either caused by the steady heat propagation by conduction, or by accelerated warming through advection (from water)
- High hydrostatic pressures at perched water tables