



Key challenges and research questions for steep rock slope permafrost investigations:

Some interesting opportunities for geophysicists ?

Florence Magnin



1. General introduction on permafrost

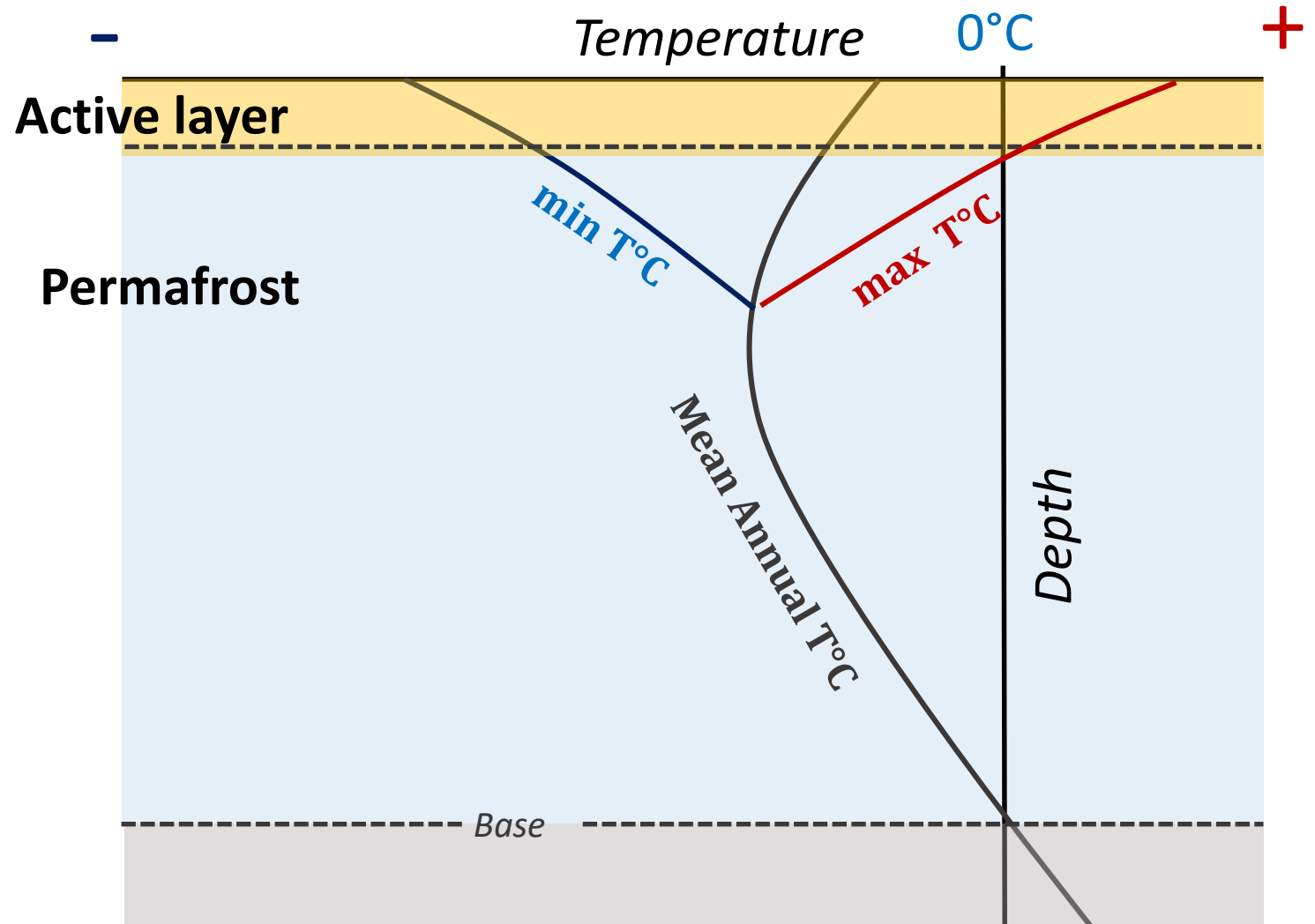
What is permafrost ?

A thermal state

- Any ground which temperature remains $< 0^{\circ}\text{C}$ for at least 2 consecutive years
- Results from a negative energy balance between the ground and the atmosphere

→ Essential Climate Variable

- Permafrost temperature
- Active layer thickness

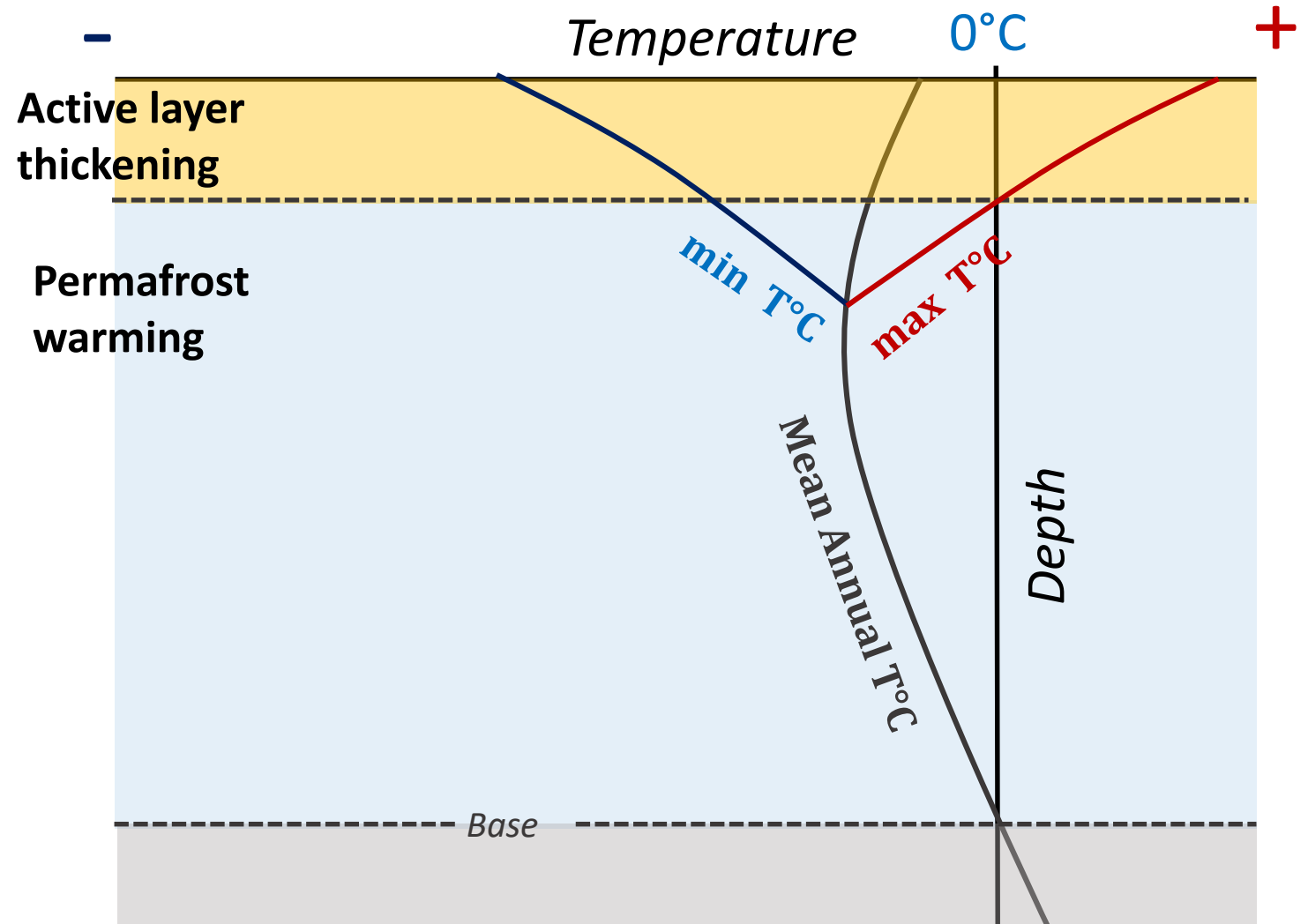


What is permafrost ?

Permafrost degradation:

- Active layer thickening
- Permafrost warming

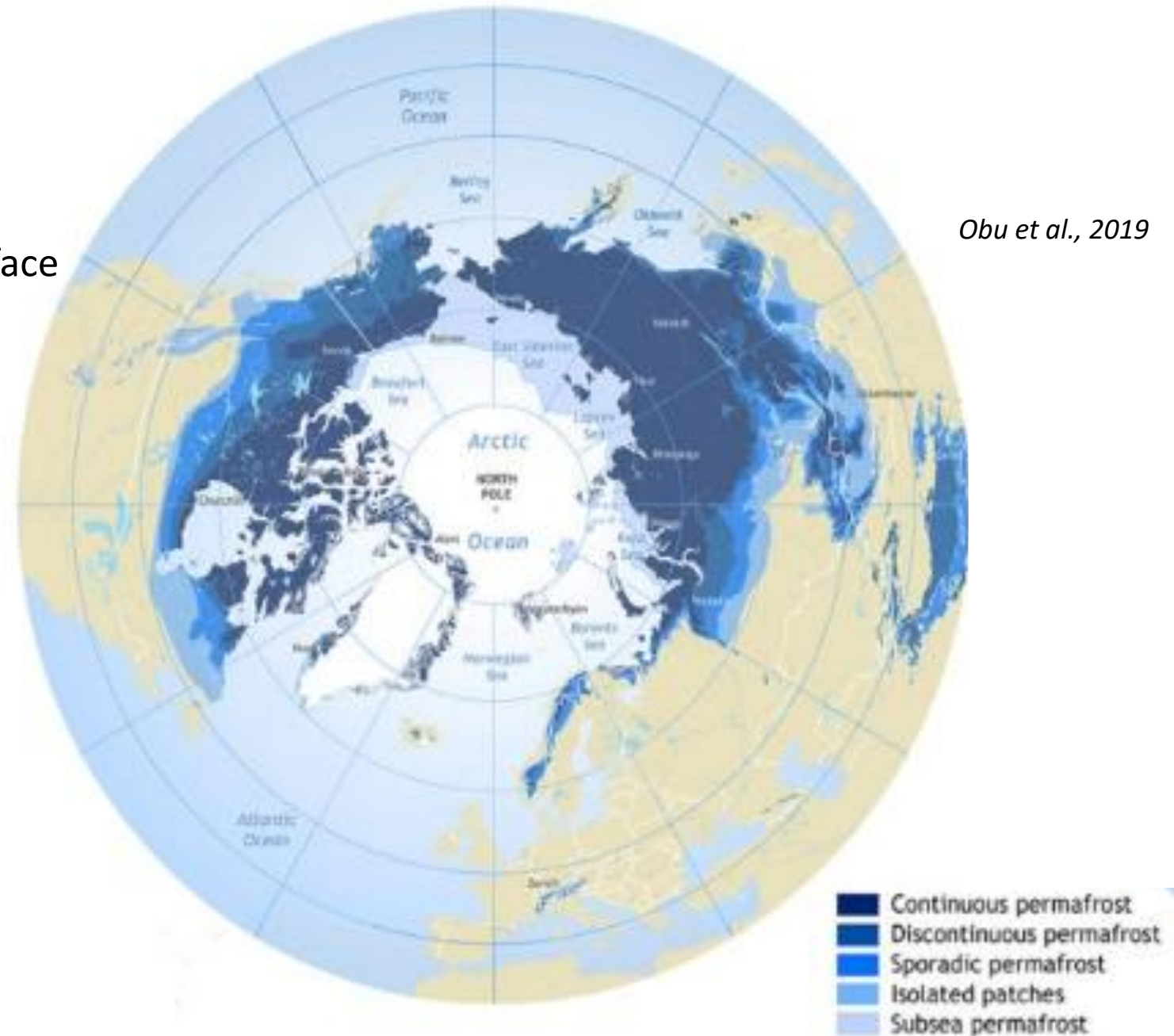
→ Many environmental and socio-economical issues



Where is permafrost ?

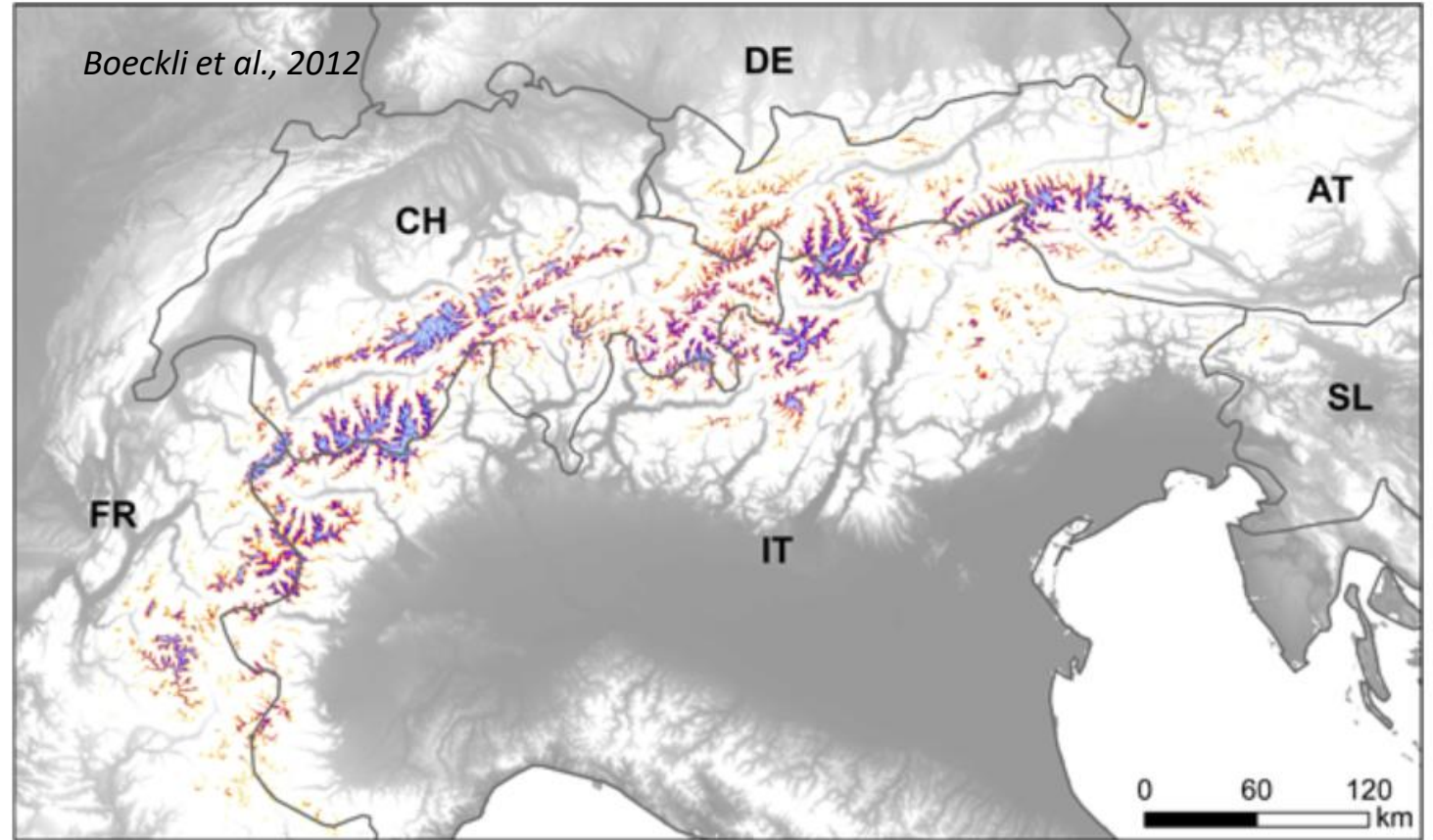
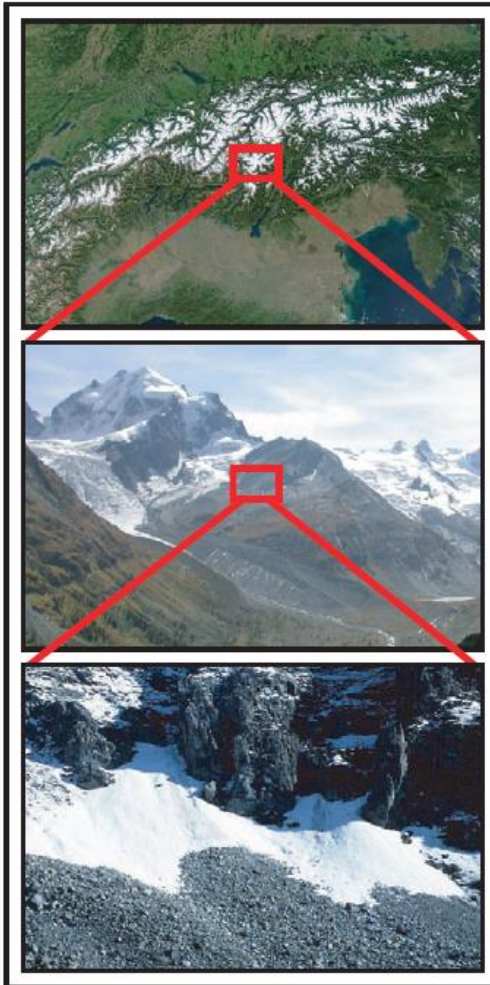
- **Continuous permafrost** : > 90 % of the surface area underlain by permafrost
- **Discontinuous permafrost** : 50 to 90 %
- **Sporadic permafrost** : 10 to 50 %
- **Isolated permafrost** : 0 to 10 %

- 15 to 22% of the continental surface area (14 to 21×10⁶ km²)



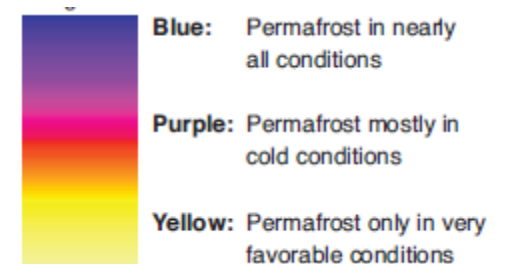
Where is permafrost ?

- 5 to 6% of the surface area (6220 km²)
- 3 times more extended than glaciers
- **Highly discontinuous in mountain areas !!!**



→ the energy balance is highly variable in space and time

Gruber, 2005





Relevance, specificities and key challenges of steep rock slope permafrost

Relevance of steep rock slope permafrost

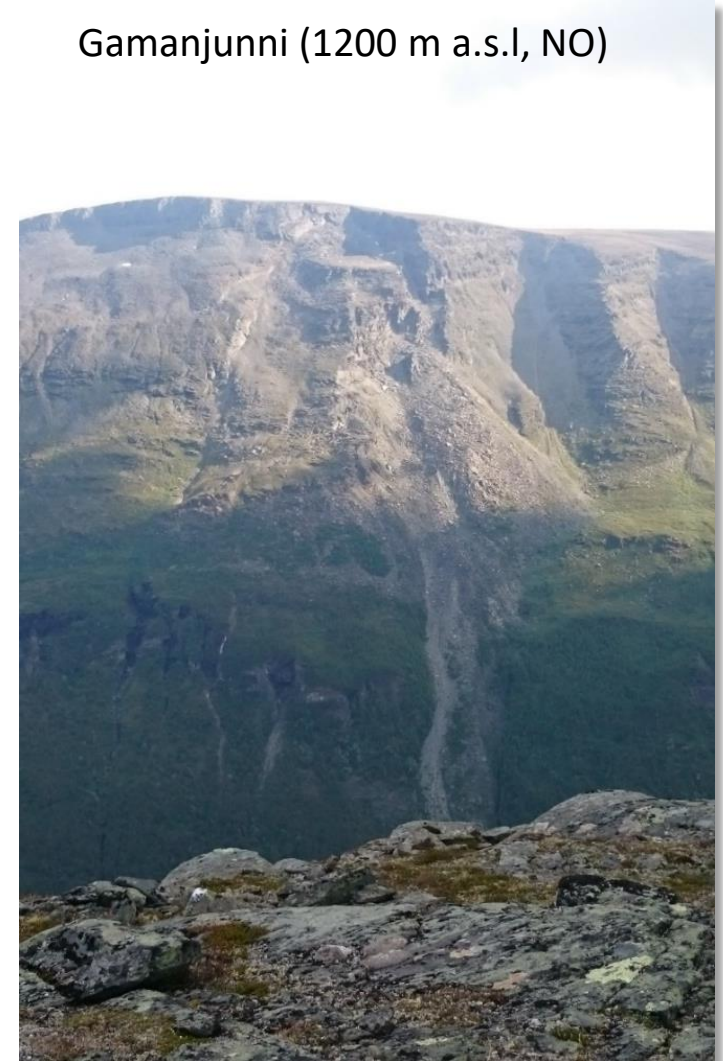
Les Drus (3754 m a.s.l., FR)



Piz Cengalo (3369 m a.s.l., CH)

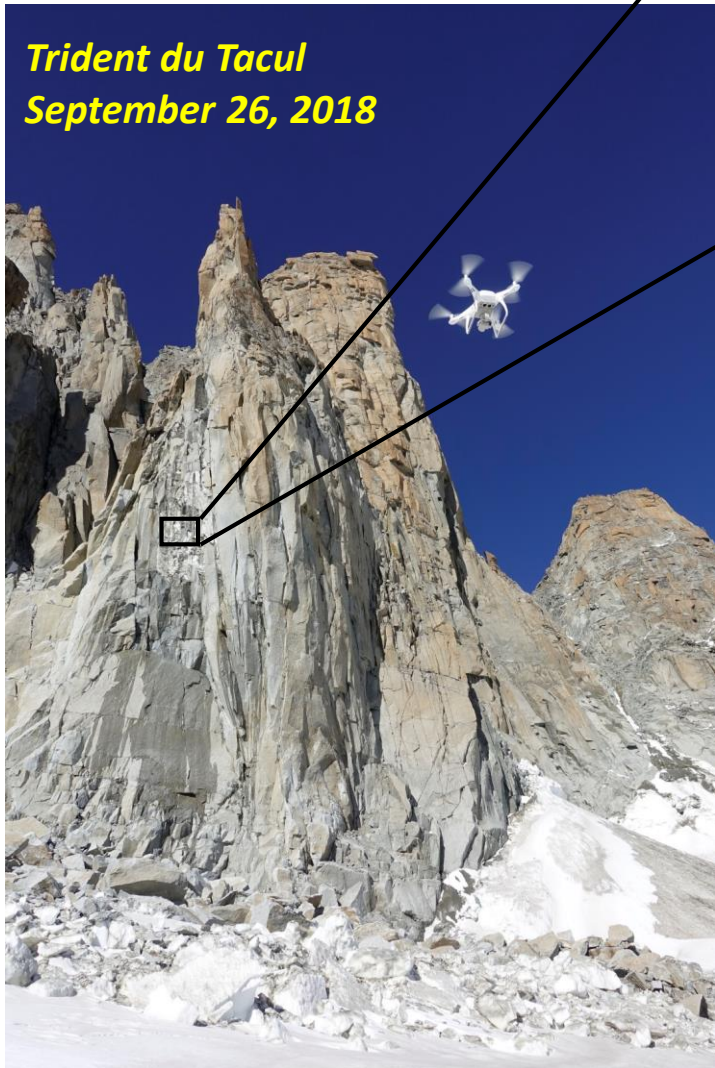


Gamanjunni (1200 m a.s.l, NO)



- Steep rock slopes are getting more and more unstable :
 - rock falls
 - rock avalanches
 - rock slides acceleration

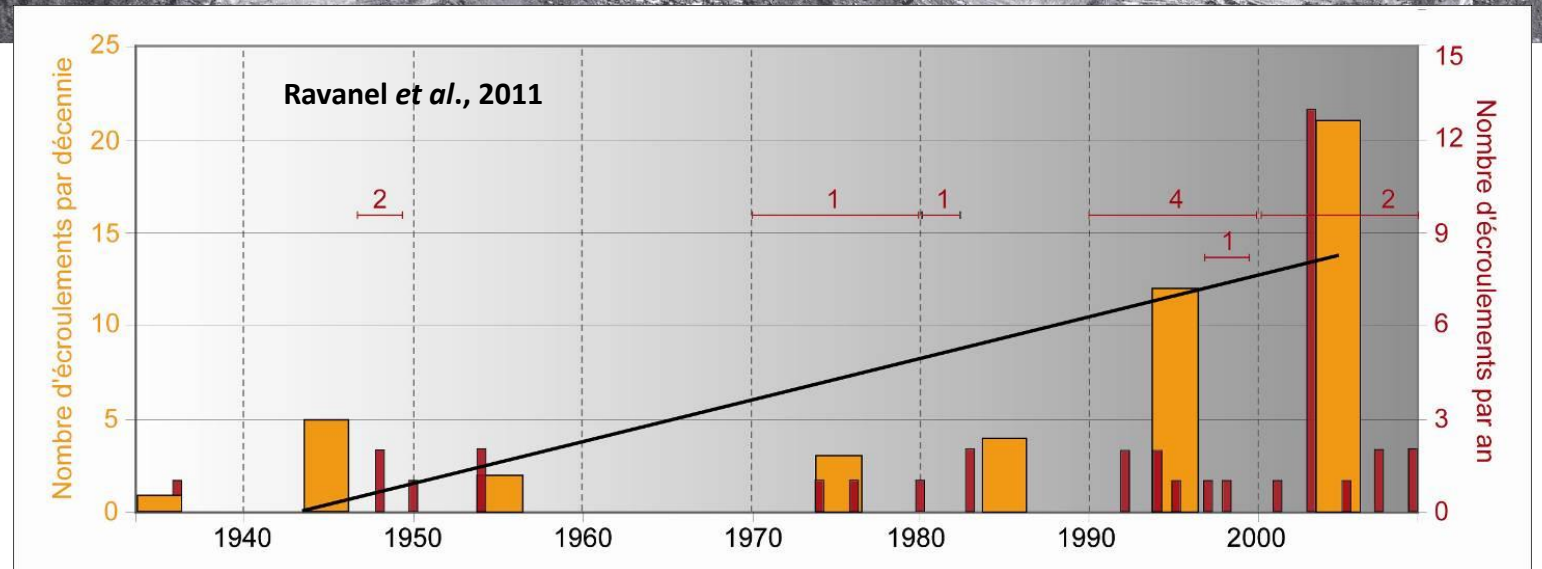
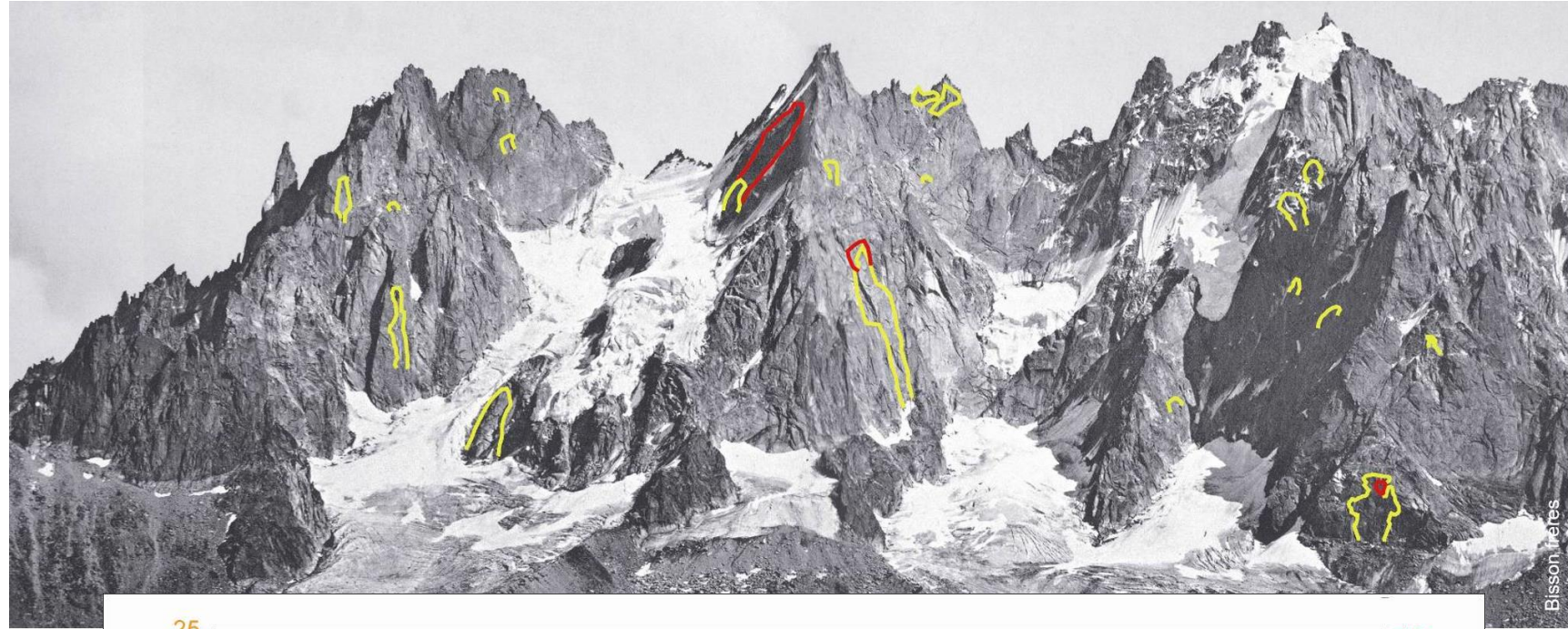
What is the link between rockfalls and permafrost degradation ?



- ➔ **The warming and melting of ice-filled fractures** = decreasing shear resistance/loss of bonding ➔ rock walls destabilization
- ➔ **Water infiltration and circulation** = (1) ice-joint erosion and/or (2) hydrostatic pressures at ice-sealed fractures ➔ rock walls destabilization

Relevance of high mountain permafrost

- High number of rockfalls is correlated with hot periods (hot decades, hot summers...)



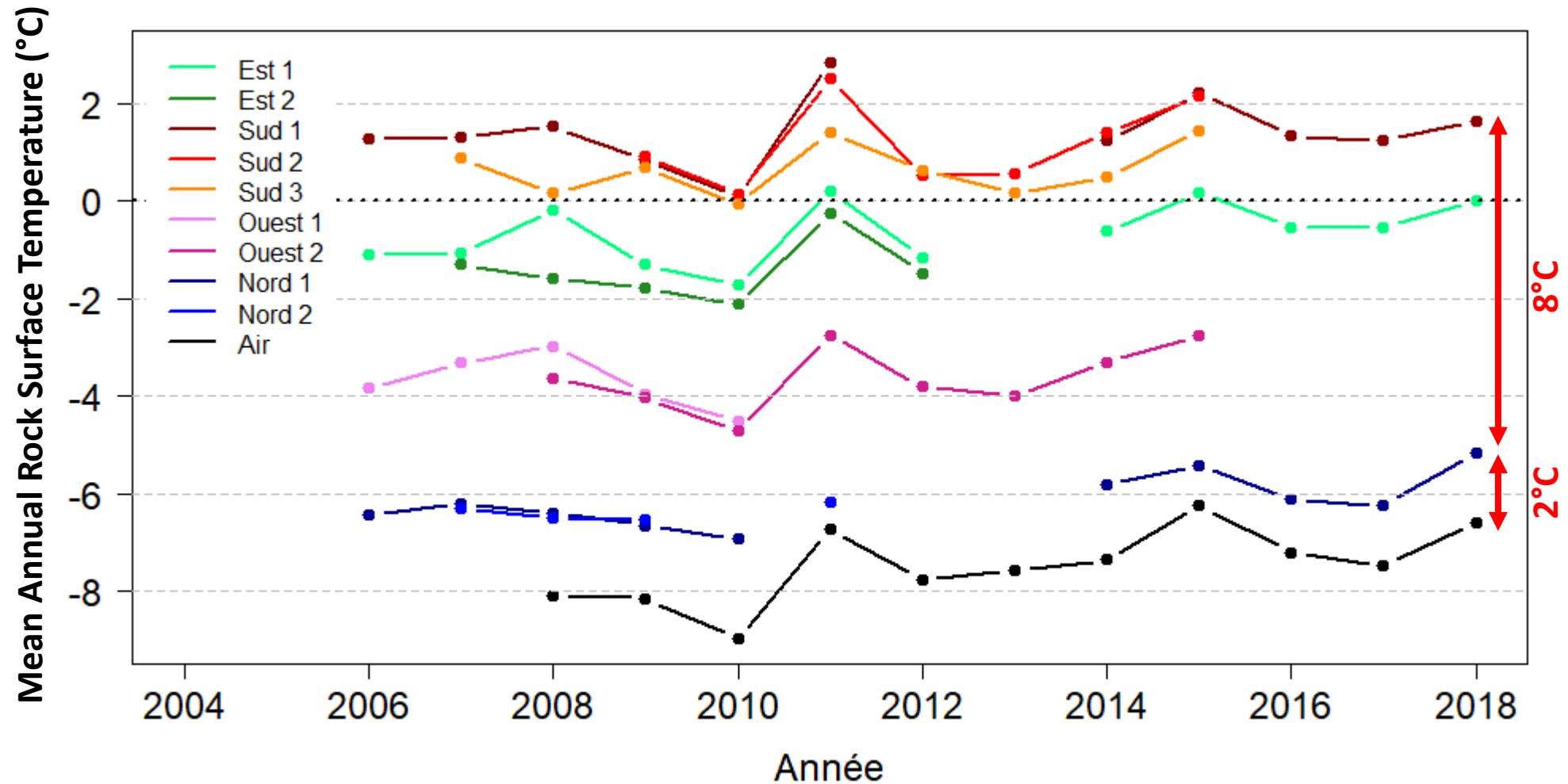
How permafrost is distributed in steep slopes ?

The Aiguille du Midi (3842 m a.s.l.)

Rock surface temperature sensors installed between 2005 and 2008 at 0.03 to 0.55 m depth



How permafrost is distributed in steep slopes ?



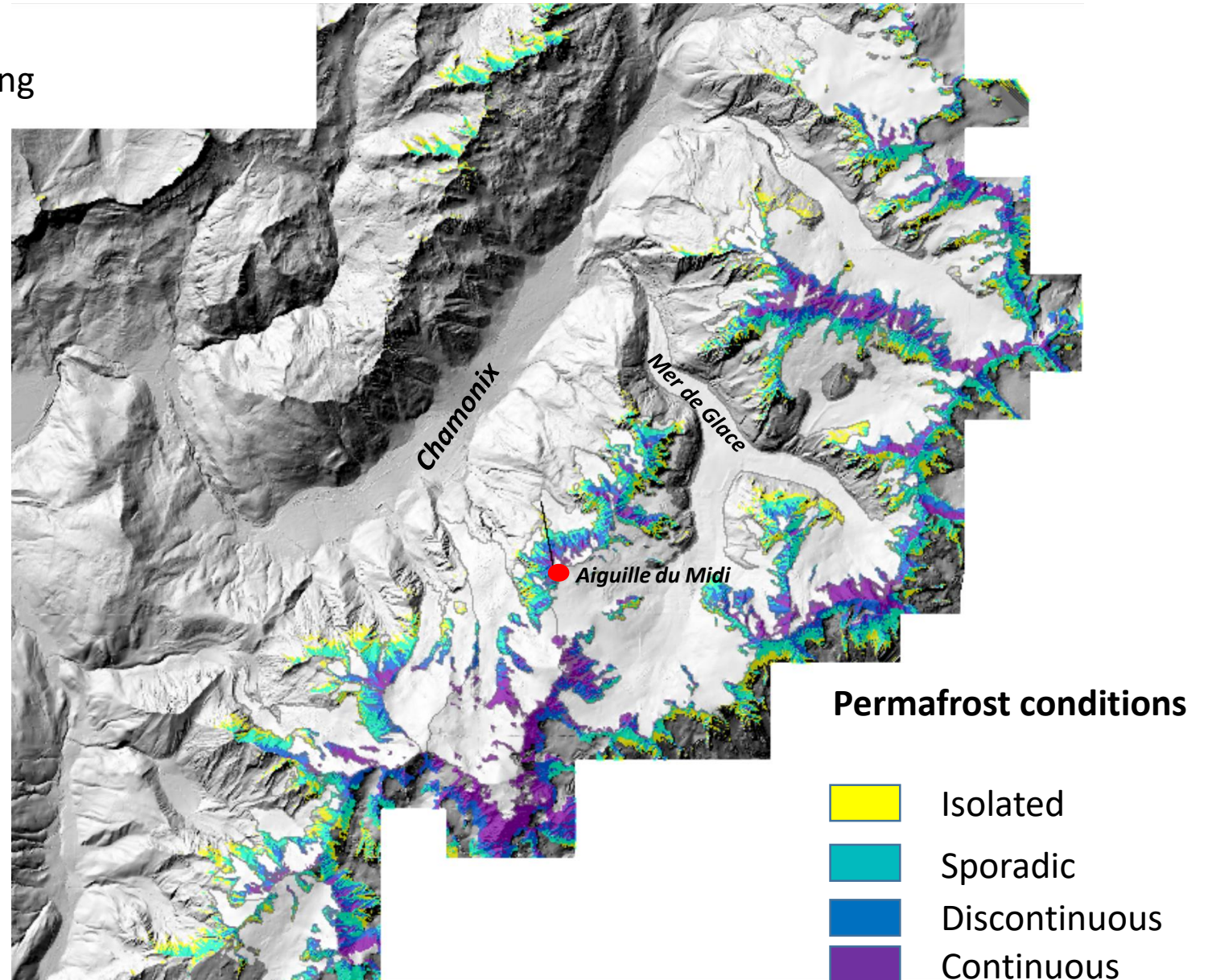
➔ Rock surface temperature = Air temperature + Incoming Solar Radiation

How permafrost is distributed in steep slopes ?

- Statistical modelling and permafrost mapping

Lower limit of permafrost :

- \approx 2500-2800 m a.s.l north faces
- \approx 3500-3800 m a.s.l. south faces



How does steep rock slope permafrost respond to climate signals ?

The Aiguille du Midi (3842 m a.s.l.)

- Three 10 m deep boreholes equipped since 2009 with thermistor chains

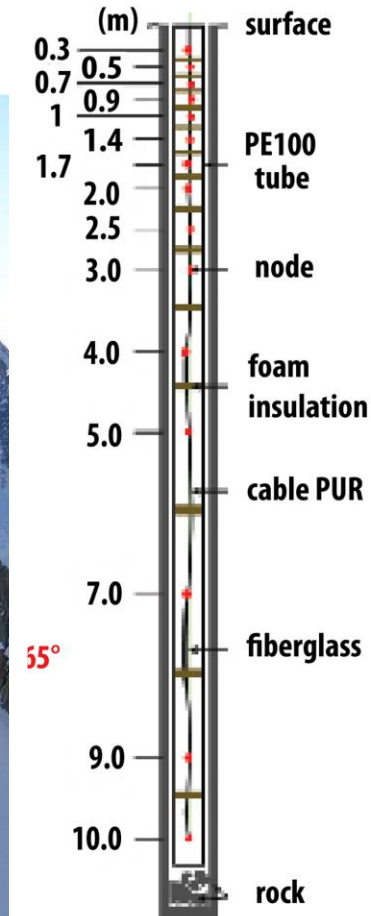
NW face



South face



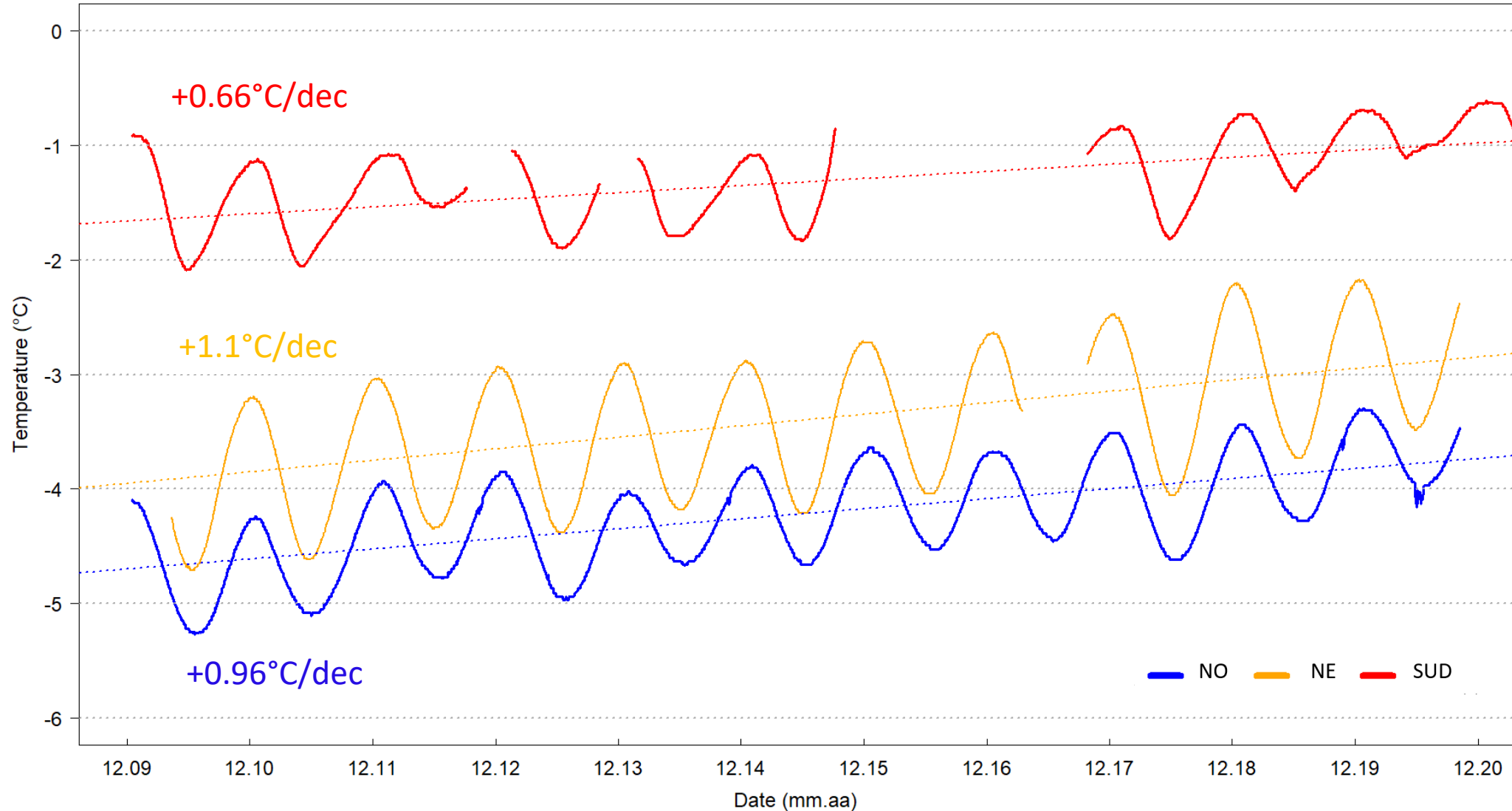
NE face



How does steep rock slope permafrost respond to climate signals ?

- Up to + 1°C per decade !!!

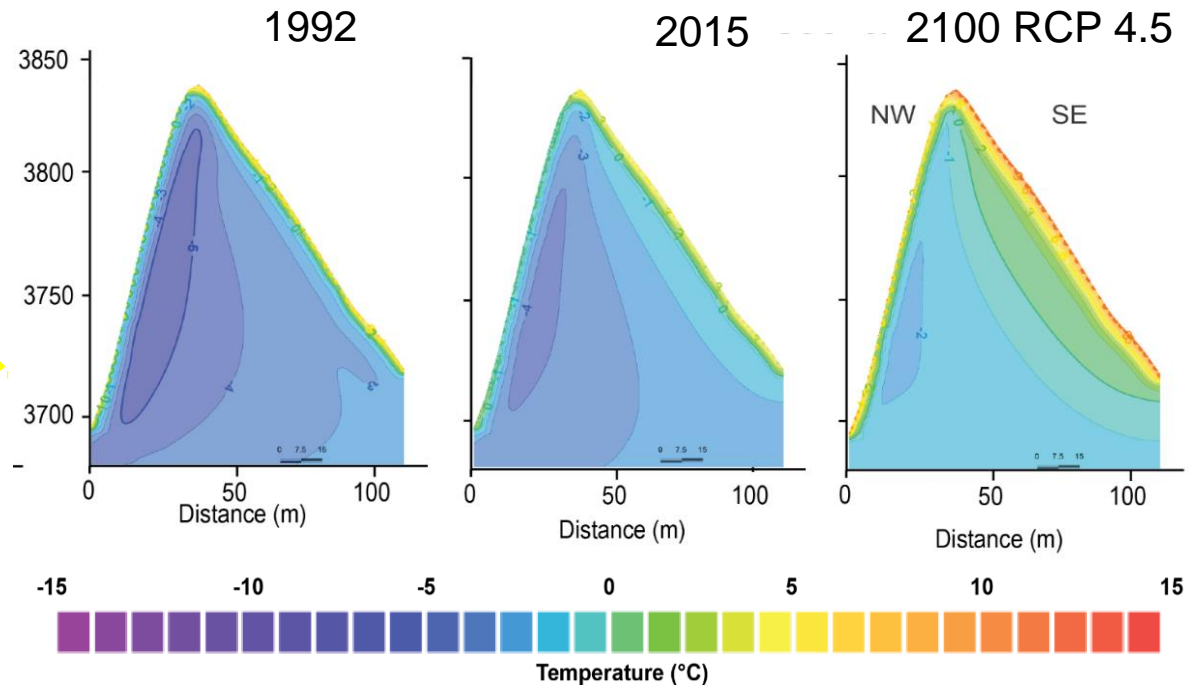
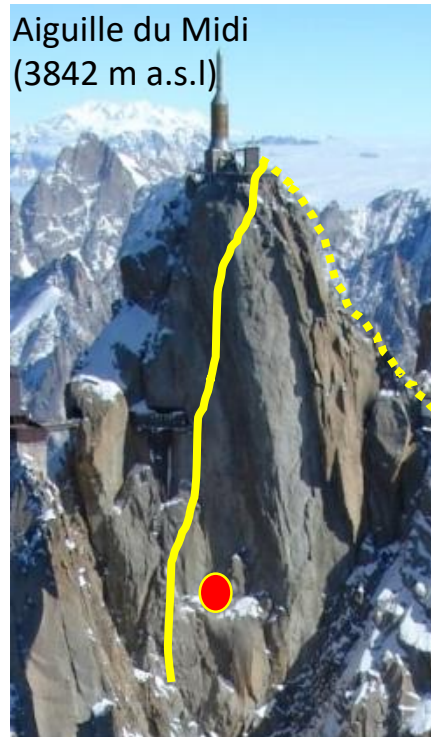
➔ More details in the program!



How does steep rock slope permafrost respond to climate signals ?

- Physic-based modelling to simulate permafrost evolution:
 - 1) Creation of surface temperature time series based on air temperature and direct solar radiation,
 - 2) Simulation of the conductive heat transfer and latent heat exchanges in a homogeneous, saturated and isotropic rock medium

➔ More details in the program!





Key challenges for steep rock slope permafrost investigations

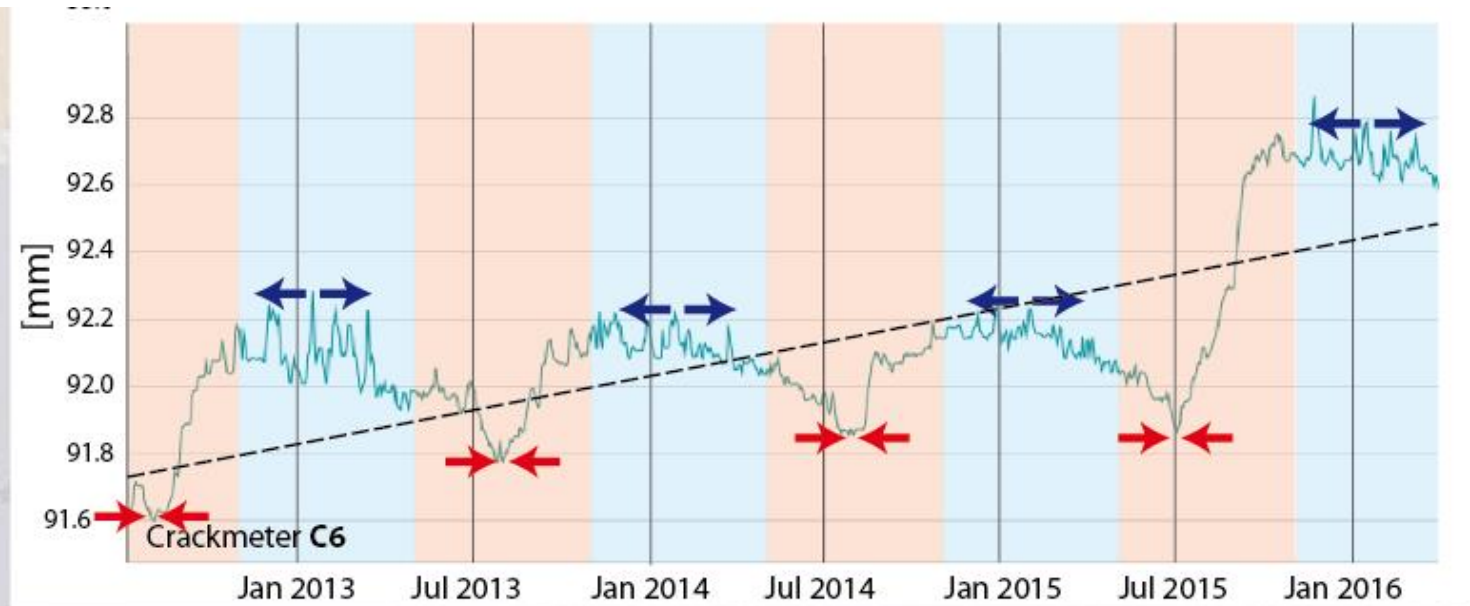
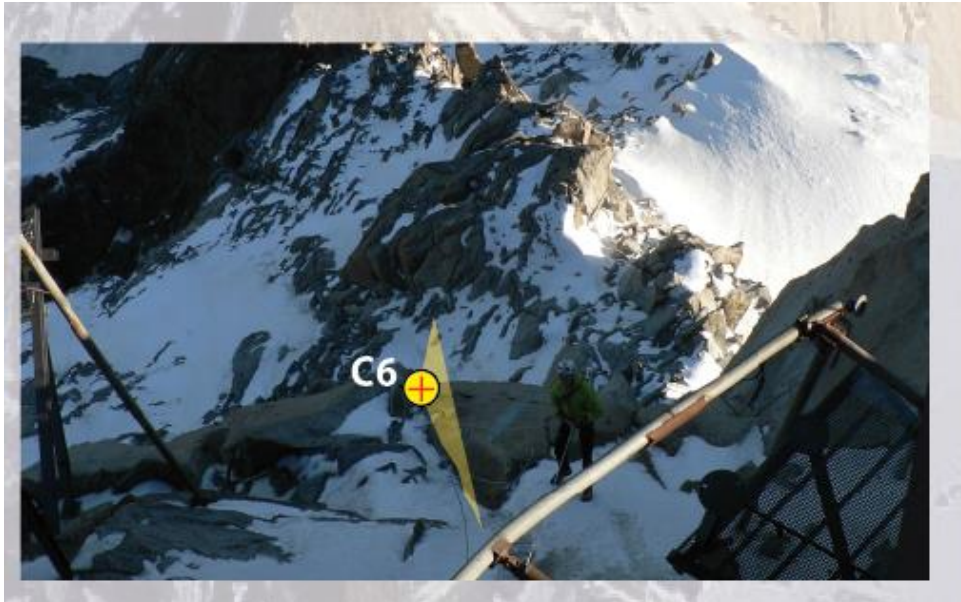
- ➔ Estimating thermal processes and mechanical behaviour in fractures

Fractures kinematics

6 crackmeters installed in 2012

→ Opening in winter and closing in summer

→ Cyclic behaviour and irreversible opening

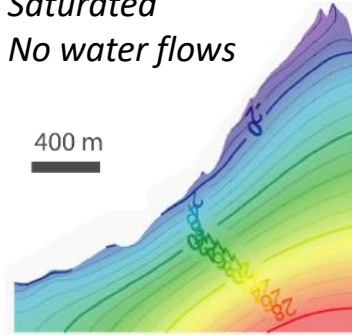


Modelling water flows into bedrock fractures

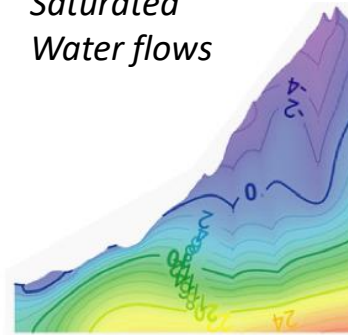
- Simulating water and heat transfers using the Darcy law calculating first water flow velocity that is then integrated in the dispersive-diffusive heat transport equation
- Simulating laminar water flows in fractures (Hagen-Poiseuille law)
- Simulations are run using the Feflow® program

Steady freezing (permafrost aggradation)

*Saturated
No water flows*



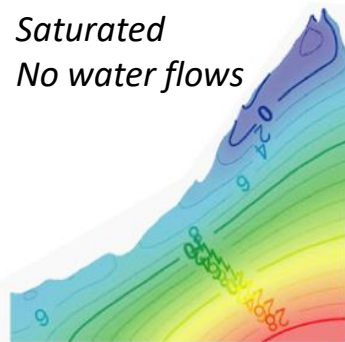
*Saturated
Water flows*



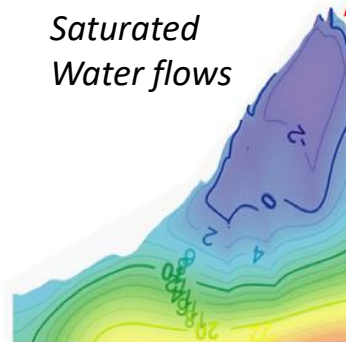
→ Deeper permafrost body and enhanced permafrost degradation

Steady thawing (permafrost degradation)

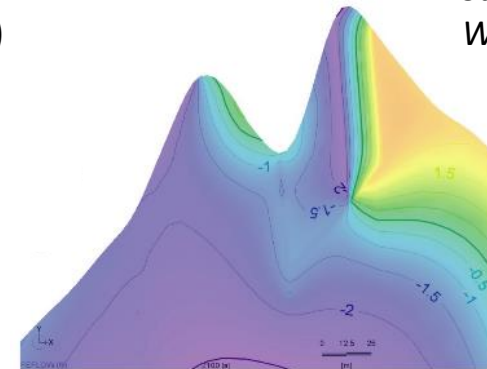
*Saturated
No water flows*



*Saturated
Water flows*

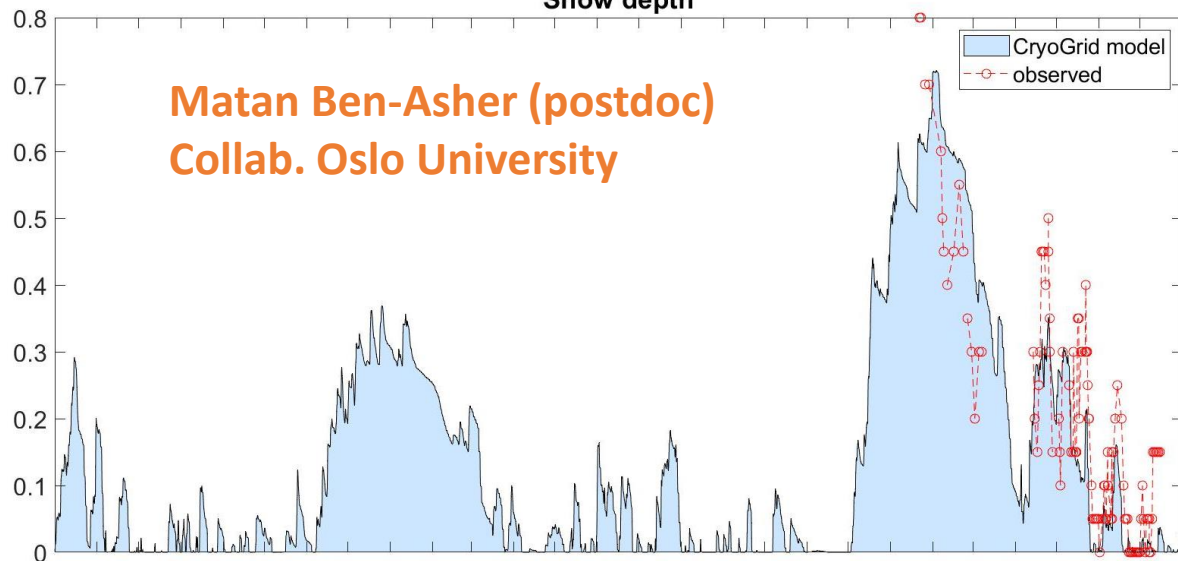


*Saturated
Water flows*

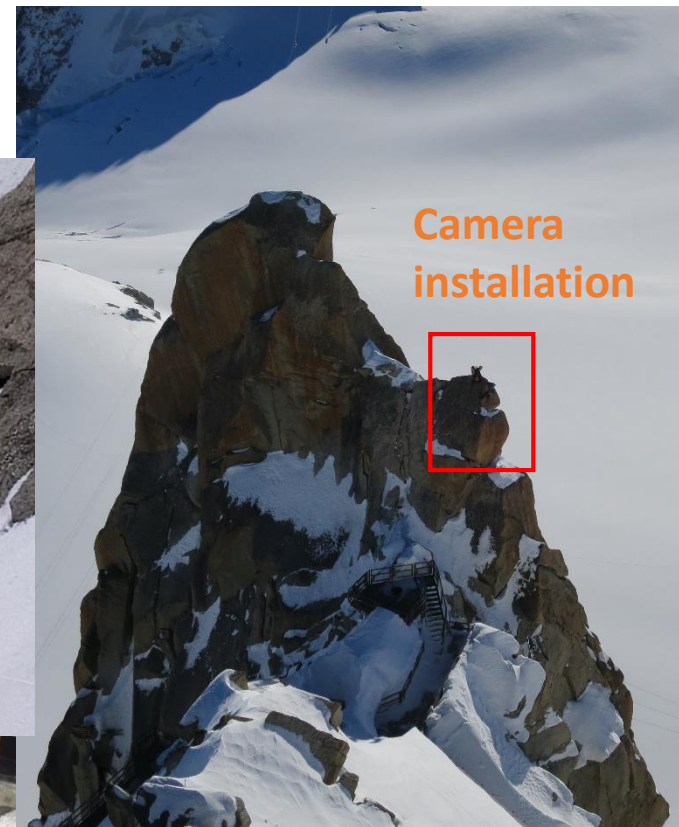
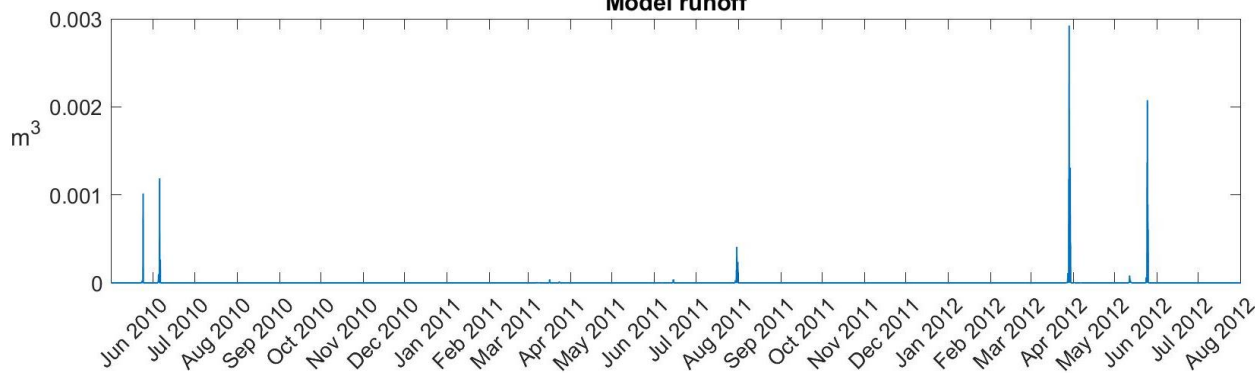


Assessing possible water input from snow melting

Snow depth



Model runoff



Collab. Styx4D
(drone surveys)

Tracking water flows in fractures



Matan Ben-Asher (postdoc)



- ➔ How much water flows through the fractures ?
- ➔ How long does it take to flow from the surface to the galleries ?
- ➔ Is it seasonal water (snow) or older water (permafrost degradation) ?

Detecting water flows and their effect with geoelectrical monitoring ?

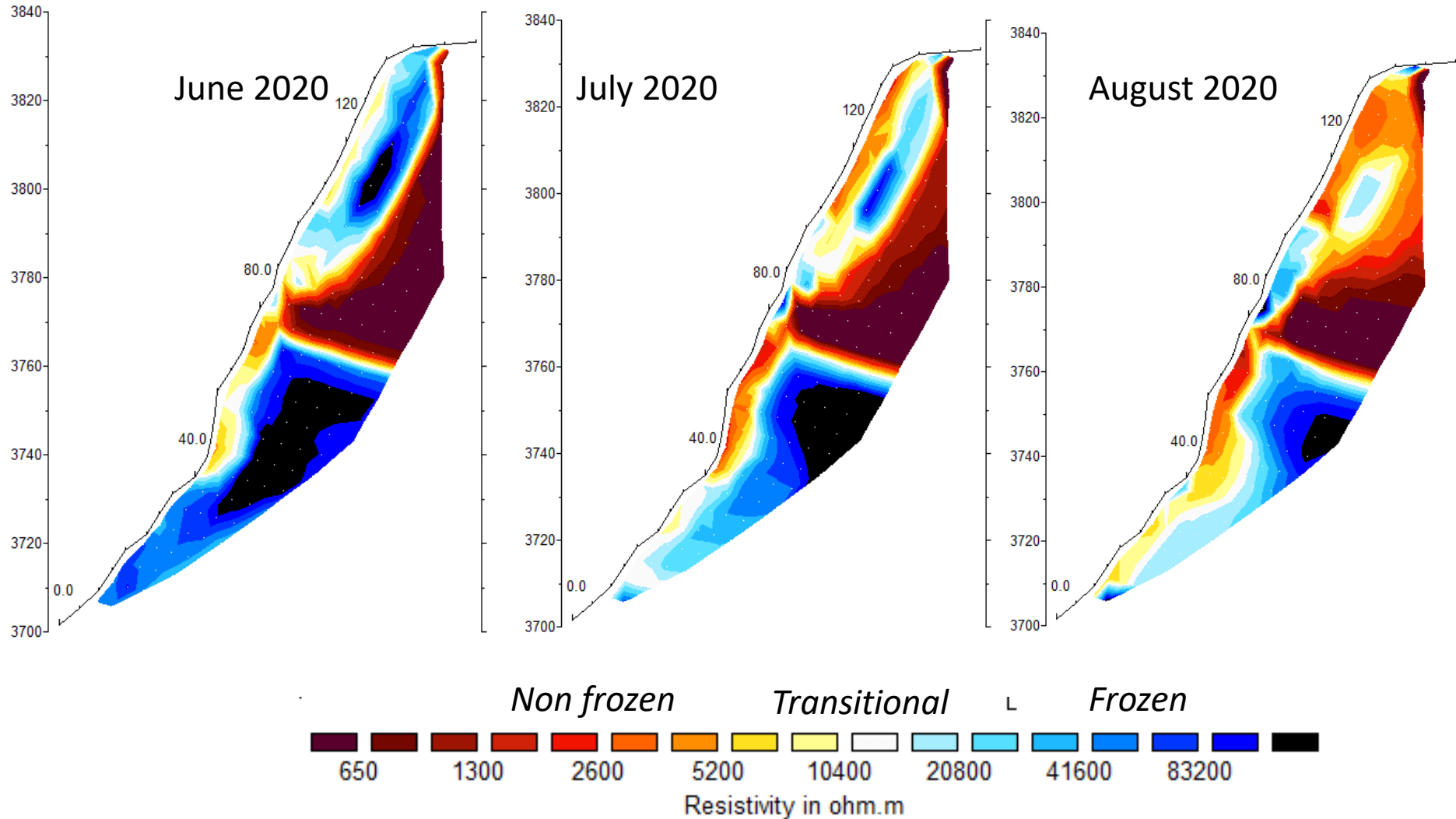


- 3 160-m long câbles
- Electrode spacing 5 m
- Attempt of automatic monitoring
- But many challenges to face....

➔ Josué Bock (postdoc)



Detecting water flows and their effect with geoelectrical monitoring ?



➔ See also presentation O22 from Duvillard et al.

- ➔ Can we detect non-conductive heat transfers ?
- ➔ Can we detected saturated/unsaturated conditions ?
- ➔ Can we detect ice infill in fractures ?

- ➔ collab. André Revil : development of petrophysical models
- ➔ Josué Bock (postdoc)

Conclusions

- High mountain (steep rock slopes) permafrost is invisible, highly variable in space
- It is directly coupled with the atmosphere and thus directly responds to Global Warming.
- Understanding its evolution has major implications for risk assessment associated to rock slope failures
- Major challenges are now associated to assessing heterogeneous conditions and anisotropic processes, notably ice-infill and water flows in fractures to improve our understanding of the thermal response to climate signal and mechanical behaviour of these rock walls
- **Could geophysics complete some of these challenges ?**



*Thank you very much
Any questions ?*