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The effects of the hot summers of 2015 & 2018 on the spatial-temporal permafrost evolution at the Zugspitze

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In the context of climate change, permafrost degradation becomes a key variable in understanding rock slope failures in high mountain areas. Warming of permafrost changes the thermal and mechanical properties of rock, effecting the stability of steep rock faces.

Electrical Resistivity Tomography (ERT) is the predominant permafrost monitoring technique in high mountain areas. Its high temperature sensitivity for frozen vs. unfrozen conditions, combined with the resistivity-temperature laboratory calibration on Wettersteinkalk (Zugspitze) (Krautblatter et al. 2010) gives us quantitative information on site-specific rock wall temperatures (Magnin *et al.* 2015).

Here, we present the effects of the hot summers of 2015 and 2018 on the spatial-temporal permafrost evolution at the Zugspitze in the realm of a 11 year monitoring program. Measurements were taken at the Kammstollen along the northern Zugspitze rock face. Two high-resistivity bodies along the investigation area reach resistivity values $\geq 10^{4.5}\,\Omega$m (~ -0.5 °C), indicating frozen rock, displaying a core section with resistivities $\geq 10^{4.7}\,\Omega$m (~ -2 °C) (Krautblatter *et al.*, 2010). Seasonal variability is seen by laterally aggrading and degrading marginal sections (Krautblatter *et al.*, 2010). The mean rock temperature of the entire core section shows a $\sim$2 months phase-shift between solar radiation forcing and thermal rock wall response. Further locally restricted short-term warming patterns along fracture zones are contributed to precipitation and percolating cleft water.

Our preliminary results are:

1. ERT-derived rock temperatures reproduce the natural temperature field in the rock wall and can be validated via a simple thermal model.
2. The $\sim$2 months phase-shift between thermal rock wall response and solar radiation forcing is attributed to the climatic signal propagation time and conductive energy transport.
3. Net solar radiation, the heat balance of the rock surface is the modulating factor of temporal rock wall temperature evolution, with water availability as an important driving factor.
4. The 11 year monitoring program enables the validation of the resistivity-temperature relationship for natural rock walls and displays seasonal and singular effects due to environmental factors and extreme weather events.
5. The hot summers of 2015 & 2018 show a significant warming over the entire rock wall and especially in local highly fractured zones through the centre of the permafrost lens. 2018 marks the year with the highest permafrost core temperatures and smallest areal extent yet recorded.

We further present an approach for a coupled thermo-geophysical model for conductive heat transfer in permafrost rock walls on local scale. We aim to link apparent resistivities, the ground thermal regime and meteorological forcing as seasonality and long-term climate change to validate the ERT and project future conditions.

Krautblatter, M., Verleysdonk, S., Flores-Orozco, A. & Kemna, A. (2010): Temperature- calibrated imaging of seasonal changes in permafrost rock walls by quantitative electrical resistivity tomography (Zugspitze, German/Austrian Alps). *J. Geophys. Res.* 115: F02003.

Magnin, F., Krautblatter, M., Deline, P., Ravanel, L., Malet, E., Bevington, A. (2015): Determination of warm, sensitive permafrost areas in near-vertical rockwalls and evaluation of distributed models by electrical resistivity tomography. *J. Geophys. Res. Earth Surf.*, 120, 745-762.