Insight into subsurface - quantification of alpine heat waves and their impact on high mountain permafrost

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In recent years the changing state of the cryosphere has been one of the most visually striking effects of climate change in mountainous terrains, gathering increased attention of not only the scientific community but the general public. Ice loss in the subsurface, caused by a warming ground thermal regime, is not directly visible such as retreating glaciers or annual snow cover changes, but it can have major impacts on ground stability.

Heat waves may contribute twofold to cryospheric changes: (1) as contributors to the general warming trend and (2) by (potentially) irreversibly changing the ground ice content through excessive amounts of heat penetrating the ground during such an event. Here, we focus on the second aspect and its impact on mountain permafrost. Although climatological research provides several tools for heat wave analysis, the application of (often regional) studies to the sparsely available borehole data and discrete meteorological monitoring networks are rare.

We employ the Heat Wave Magnitude Index daily (HWMId) metric to analyse temperature data from several Swiss Permafrost Monitoring Network (PERMOS) and MeteoSwiss stations near well-studied permafrost monitoring sites in the Alps. Historical and reconstructed data are used to determine specific temperature thresholds per site, accounting for local conditions (such as geomorphology, geology or ice content) therefore a systematic heat wave definition can be applied uniformly across all locations.

HWMId is compared to the changes in ground moisture content and observed changes in the permafrost body derived from borehole data. In addition, ice content is independently estimated from time series of 2-dimensional geophysical data, namely seismic refraction tomography and electrical resistivity tomography jointly inverted by petrophysical joint inversion. Initial results from the analysis of decade-long time series show correspondence between ground resistivity decrease with a general increasing trend in heat wave occurrences and intensity. Moreover, heat waves precondition the permafrost for further thawing in subsequent years. Resilience of permafrost to the heat wave events in different landforms brings important implications for slope stability and safety of communities and infrastructure in mountainous regions.

I. Definition - Heatwave Magnitude Index daily (Russo et al. 2015)

1. Is it a Heatwave day?

For given n-th day of a year

$$T_{n-15}, \dots, T_n, \dots, T_{n-15}$$

90th rolling percentile centred on T_n

$$T_{n\_90th}$$

For all n-th days in 30 years reference period 1981-2010

$$\text{Average}\,(T_{1981n\_90th} + T_{1982n\_90th} + \dots + T_{2009n\_90th} + T_{2010n\_90th})$$

Heatwave day – yes/no

$$T_{AVGn\_90th} < T_n \qquad\qquad T_{AVGn\_90th} > T_n$$

2. Are there at least 3 consecutive days where $T_{AVGn\_90th} < T_n$?

If yes, calculate HWMId, otherwise no heatwave

$$HWMId = \frac{Tn - Tn\_75th}{Tn\_75th - Tn\_25th}$$

Using 25th and 75th rolling percentile

3. Sum up HWMId of each consecutive heatwave day to yield the cumulative magnitude of a heatwave

II. Dataset

HWMId definition was applied to the dataset from **7 different high mountain observatories** (Fig.1), with special focus in this contribution on 3 sites. **30-year reference period** was chosen to be 1981-2010, with data analysed between **1981-2023** (with an exception for Murtèl-Corvatsch 1982-2021). Due to scarcity of long term observed meteorological data at the permafrost monitoring sites, several parameters, notably air temperature and precipitation, were **reconstructed using quantile mapping** approach (Rajczak et al. 2016). Number of heatwaves detected at those sites according to the original 3-day long definition (Russo et al. 2015) was significantly high (Fig.4e), and proved to be difficult to fully analyse such dataset. Further window lengths were tested, to focus only on most significant events resulting in choice of at least **5 consecutive days** meeting requirements discussed in section I. Definition (Fig.4f).

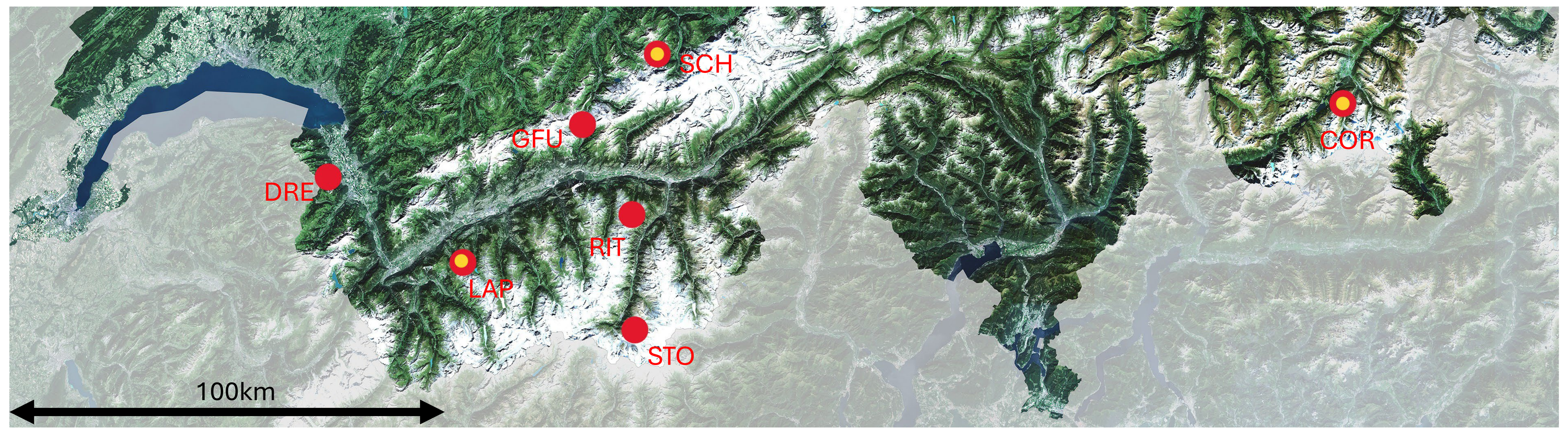

Fig.1 Locations of the stations used in the study. Yellow markers signal stations with the heatwaves presented on the right panel of the poster. Code names of stations : SCH-Schilthorn, COR-Murtèl-Corvatsch, LAP-Lapires, DRE-Dreveneuse, STO-Stockhorn, RIT-Ritigraben, GFU – Gemmi Pass. Satelite photo courtesy of ESA.

Fig.2 Field photograph on the Northeast slopes of Schilthorn

Fig.3 Field photograph of destroyed measurement station at Murtèl-Corvatsh

Schilthorn	Lapires	Murtèl-Corvatsch
2909m asl	2500 m asl	2670 m asl
Fine talus slope	Course blocky talus slope	Rock glacier
Facing Northeast	Facing Northeast	Facing Northwest

Tab.1 Summary of the field conditions at 3 sites

III. Results

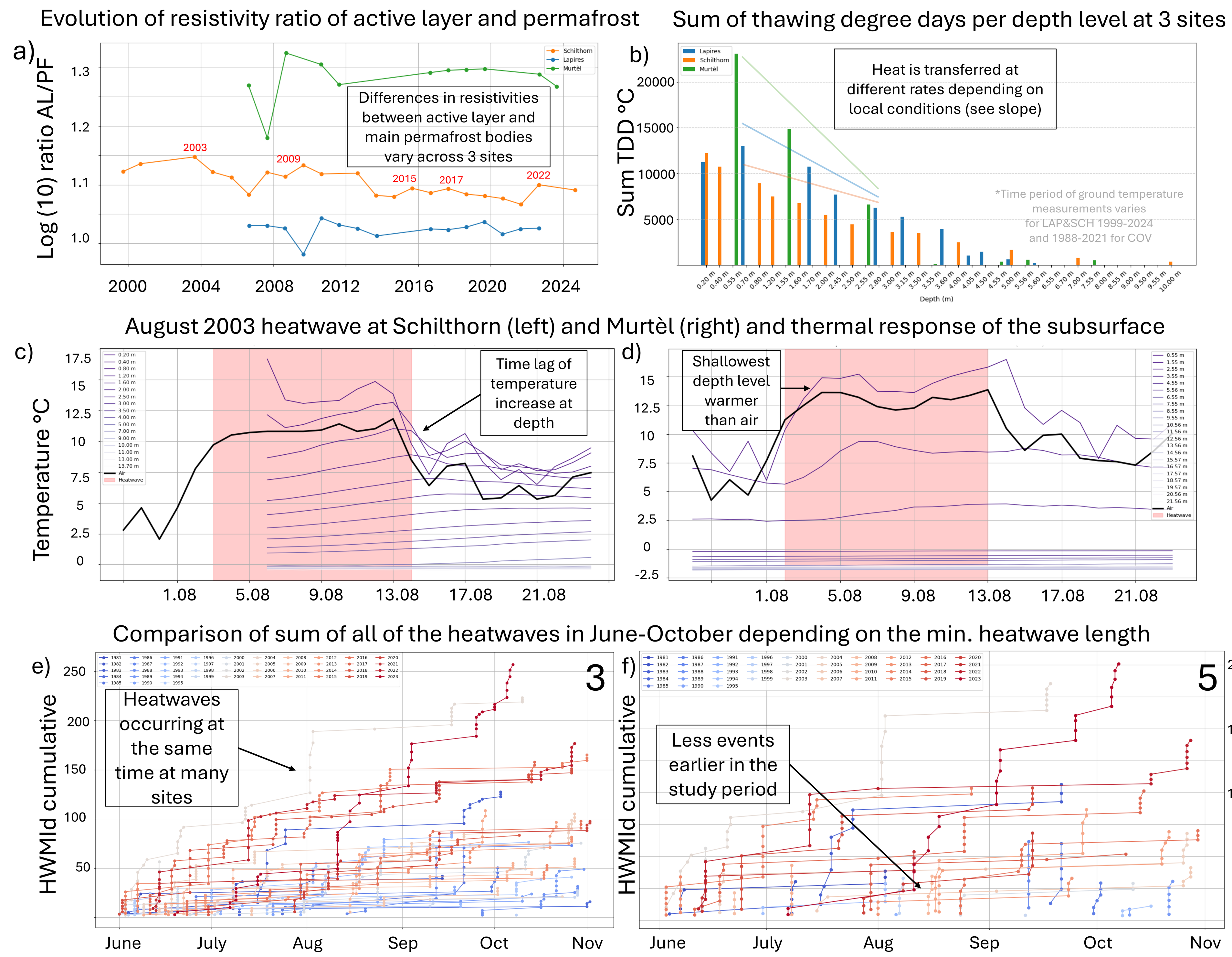

Fig.4 a) Resistivity ratio between active layer and permafrost at Schilthorn, Lapires and Murtèl, over monitoring periods. Following method as described by Hauck and Hilbich (2024), resistivity values were taken from the inverted ERT model at the borehole locations and plotted as ratios between permafrost and active layer respective to the site. Notable heatwaves years marked. b) Thawing degree days for different depths of borehole measurements for LAP, SCH and COR. At each site heat is transferred at a different rate. c) Schilthorn and d) Murtèl ground temperature responses to heatwave in August 2003 (the most significant of all the heatwaves in the studied dataset). The lighter the shade of purple, the deeper the measurement depth. Air temperature marked in black. Cumulative HWMId over the studied period 1981-2023 for original 3 day long definition e), as well as window-length- adjusted f) 5 day HWMId.

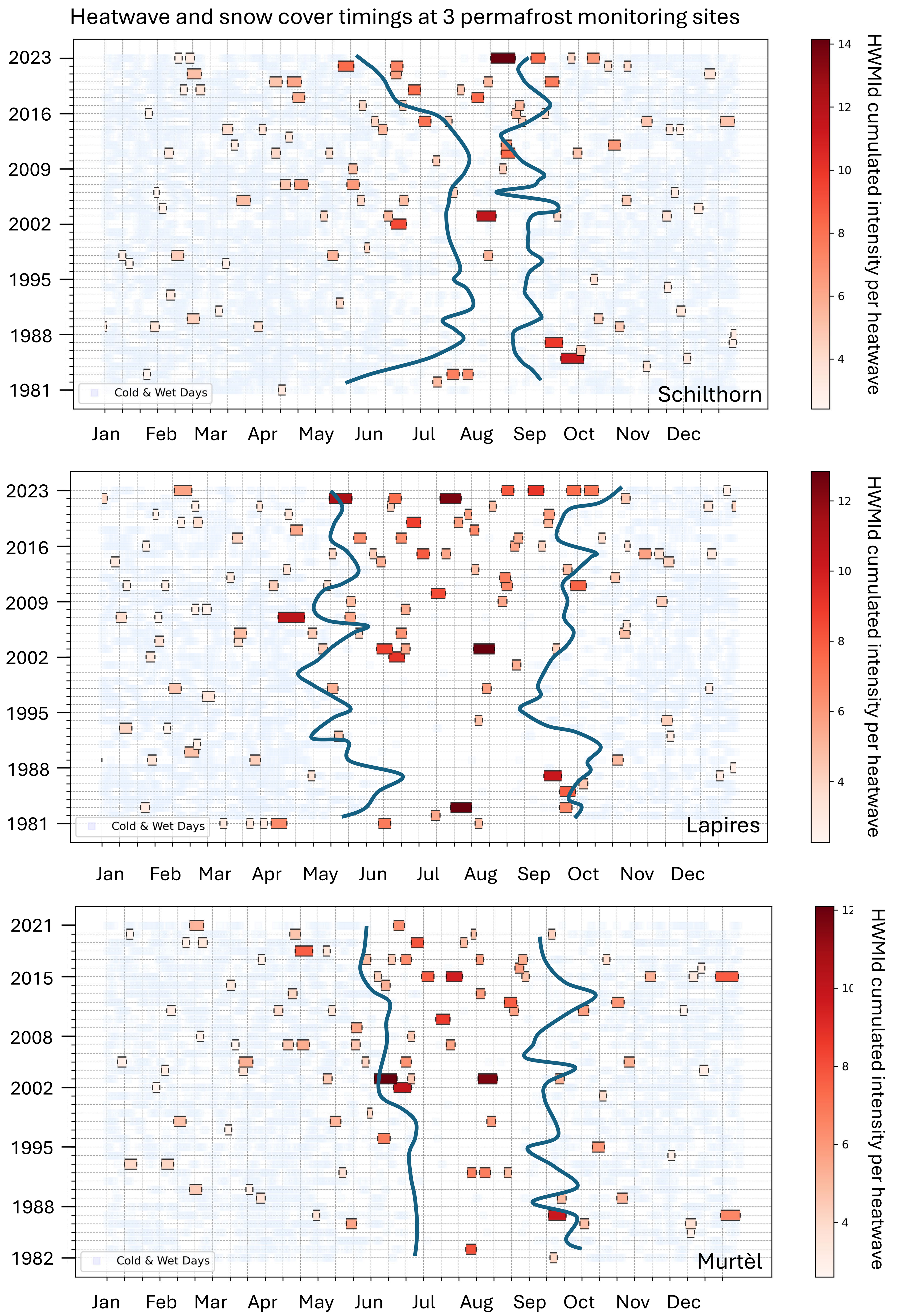

Fig.5 Heatwaves timing and cumulated HWMId at 3 high mountain permafrost sites. Due to lack of consisted snow cover data, periods below 0.5deg Celsius and with daily precipitation higher than 0.05cm were marked with light blue to indicate the extend of snow cover. Onset and end of snow cover marked in dark blue to highlight potential period when the atmosphere is coupled to the ground.

IV. Discussion and Outcomes

1. Most heatwaves are occurring at the same time throughout Swiss Alps – controlled by larger atmospheric fronts rather than local conditions.
2. Timing and intensity remains in the same range of values regardless of the elevation above sea level, HWMId is normalised to make different sites comparable.
3. Depending on the geomorphology and local petrophysical conditions (also controlled by parameters such as block size or geology), temperature signal from the air measurement penetrates the ground at different rates (Fig 4b,c,d.)
4. Melting of the ice, as well as drying and wetting of the upper layer can be detected by geophysical measurements.

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Satelite image of Switzerland (ESA): https://www.esa.int/ESA_Multimedia/Images/2016/12/Switzerland

Abstract

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