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Swiss Permafrost Monitoring Network PERMOS

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Edited by

Jeannette Noetzli, PERMOS Office, WSL Insitute for Snow and Avalanche Research SLF, Davos Dorf
Cécile Pellet, PERMOS Office, Department of Geosciences, University of Fribourg, Fribourg

Reviewed by

Members of the PERMOS Scientific Committee: Alessandro Cicoira, Chantal Del Siro, Reynald Delaloye, Daniel Farinotti, Robert Kenner, Christophe Lambiel, Coline Mollaret, Cristian Scapozza.

Data collection

The maintenance of field installations and the data acquisition at the PERMOS sites is the responsibility of the PERMOS Partner Institutions: ETH Zurich (ETHZ), Universities of Fribourg (UniFR), Lausanne (UniL) and Zurich (UZH), University of Applied Sciences and Arts of Southern Switzerland (SUPSI), and WSL Institute for Snow and Avalanche Research SLF (WSL-SLF.)

Citation

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Data availability

All PERMOS data are subject to the PERMOS Data Policy (open access for non-commercial use) and available online https://www.permos.ch/data-portal. This report is based on the PERMOS data set doi: 10.13093/permos-2023-01.

Cover page

Drilling of a new borehole in the frozen moraine at Gentianes (VS) in Summer 2022 to secure the 20-year permafrost temperature time series. Photo: C. Lambiel.

List of abbreviations

ALT	Active layer thickness
ERT	Electrical resistivity tomography
ECV	Essential Climate Variable
FOEN	Federal Office for the Environment
GCOS	Global Climate Observing System
GCW	Global Cryosphere Watch
GFI	Ground Freezing Index
GTI	Ground Thawing Index
GTN-P	Global Terrestrial Network for Permafrost
GST	Ground surface temperature
MAAT	Mean annual air temperature
MAGST	Mean annual ground surface temperature
rMAGST	Running mean annual ground surface temperature
MAPT	Mean annual permafrost temperature
MeteoSwiss	Federal Office of Meteorology and Climatology
PERMOS	Swiss Permafrost Monitoring Network
RGV	Rock glacier velocity
SCNAT	Swiss Academy of Sciences
TGS	Terrestrial geodetic survey

Summary

The Swiss Permafrost Monitoring Network PERMOS documents the state and changes of permafrost in the Swiss Alps based on field measurements of ground temperatures, electrical resistivities and rock glacier velocities. More than 20 years of data documented a general trend of permafrost warming and degradation in the Swiss Alps. Spatial variability related to site characteristics and shorter-term variations due to meteorological conditions also exist.

The mean annual air temperature in the hydrological year 2022 (October 2021 to September 2022) was around 1.5 °C above the long-term mean 1981–2010, making it the second warmest hydrological year ever measured in Switzerland. Air temperatures were above average for most of the year and in winter below-average snow heights were measured, especially in the South. The snow cover disappeared earlier than usual.

As a result of these meteorological conditions, the mean annual ground surface temperature (MAGST) of the hydrological year 2022 increased for all sites and landforms compared to the previous year. At loose-debris sites, such as talus slopes and rock glaciers, MAGST was about 1 °C higher than in the hydrological year 2021. The warmer conditions at the surface resulted in thicker active layers (ALT) in 2022 compared to 2021, with new record values measured for two thirds of the boreholes. All ALT recorded in 2022 were at or close to the maximum of the time series. At 10 m depth, the mean annual permafrost temperature in 2022 decreased by a few tenth of a °C for the most of the sites, which is considered a delayed response to the lower ground surface temperatures observed in 2021. At greater depth of 20 m, permafrost temperatures remained stable or continued to increase compared to the previous year. At some sites, new record values have been reached.

The permafrost resistivities measured in 2022 decreased at all sites by between 1.5 and 20%, reaching record low values at some sites. This indicates a general increase in liquid water content within the permafrost layer, which is considered a direct consequence of ground ice degradation.

Following the decrease of permafrost temperatures at a depth of ca. 10 m in 2022, the observed rock glaciers strongly decelerated with an average velocity decrease of –34% compared to 2021 and a maximum decrease of –87% at Yettes-Condjà in Valais. The surface velocity of rock glaciers indirectly reflects the evolution of the thermal regime of permafrost between the permafrost table and the shear horizon: When permafrost temperatures increase, rock glaciers generally accelerate.

Overall, the hydrological year 2022 was characterized by extremely warm conditions at the surface and in the uppermost meters of the ground, yielding high level or record ALT and a general permafrost resistivity decrease. At 10m depth, the delayed effect of the cold near-surface conditions observed in 2021 lead to a slight decrease of permafrost temperatures and to a marked decrease in rock glacier velocities. At larger depth, in response to long-term climatic changes, permafrost temperatures continued to increase or remained stable.

Zusammenfassung

Das Schweizerische Permafrostmessnetz PERMOS dokumentiert den Zustand und die Veränderungen des Permafrostes in den Schweizer Alpen anhand von Feldmessungen der Permafrosttemperaturen, elektrischem Widerstand und der Geschwindigkeit von Blockgletschern. Mehr als 20 Jahre Daten dokumentieren einen generellen Trend der Permafrosterwärmung und -degradation in den Schweizer Alpen. Dazu gibt es räumliche Schwankungen, die mit den Standortmerkmalen zusammenhängen, und kurzfristige Schwankungen aufgrund meteorologischer Bedingungen.

Die mittlere Jahreslufttemperatur im hydrologischen Jahr 2022 (Oktober 2021 bis September 2022) lag rund 1.5 °C über dem langjährigen Mittel 1981–2010 und war damit das zweitwärmste jemals in der Schweiz gemessene hydrologische Jahr. Die Lufttemperaturen waren die meiste Zeit des Jahres überdurchschnittlich hoch und im Winter wurden vor allem im Süden unterdurchschnittliche Schneehöhen gemessen. Die Schneedecke verschwand früher als üblich.

Als Folge dieser meteorologischen Bedingungen stieg die mittlere jährliche Bodenoberflächentemperatur (MAGST) des hydrologischen Jahres 2022 für alle Standorte und Landformen im Vergleich zum Vorjahr an. An Standorten mit losem Material an der Oberfläche, wie Schutthalden und Blockgletscher, war die MAGST um etwa 1 °C höher als im hydrologischen Jahr 2021. Die wärmeren Bedingungen an der Oberfläche führten auch zu mächtigeren Auftauschichten (ALT) im Jahr 2022 im Vergleich zu 2021, wobei bei zwei Dritteln der Bohrlöcher neue Rekordwerte gemessen wurden. Alle im Jahr 2022 gemessenen ALT lagen am oder nahe dem Maximum der Zeitreihe. In 10 m Tiefe sank die mittlere jährliche Permafrosttemperatur im Jahr 2022 an den meisten Standorten um einige Zehntel °C, was eine verzögerte Reaktion auf die im Vorjahr gemessenen tieferen Oberflächentemperaturen ist. In einer Tiefe von 20 m und mehr blieben die Permafrosttemperaturen stabil oder stiegen im Vergleich zum Vorjahr weiter an. An einigen Standorten wurden auch neue Rekordwerte erreicht.

Der 2022 gemessene Permafrostwiderstand sank an allen Standorten um 1.5–20 % und erreichte an einigen Standorten Rekordtiefstwerte. Dies deutet auf einen allgemeinen Anstieg des Flüssigwassergehalts in der Permafrostschicht hin, der als direkte Folge des Abbaus von Eis im Permafrost angesehen wird.

Nachdem die Permafrosttemperaturen in einer Tiefe von ca. 10 m im Jahr 2022 etwas gesunken sind, haben sich die beobachteten Blockgletscher stark verlangsamt mit einer durchschnittlichen Geschwindigkeitsabnahme von –34% im Vergleich zu 2021 und einer maximalen Abnahme von -87% in Yettes-Condjà im Wallis. Die Oberflächengeschwindigkeit der Blockgletscher spiegelt indirekt die Entwicklung des thermischen Regimes des Permafrostes zwischen dem Permafrostspiegel und dem Scherhorizont wider: Wenn die Permafrosttemperaturen ansteigen, beschleunigen sich die Blockgletscher im Allgemeinen.

Insgesamt war das hydrologische Jahr 2022 geprägt von extrem warmen Bedingungen an der Oberfläche und in den obersten Metern, was zu einem mächtigen Auftauschichten und einem allgemeinen Rückgang des Permafrostwiderstands führte. In 10 m Tiefe führte die verzögerte Wirkung der im Jahr 2021 beobachteten kalten oberflächennahen Bedingungen zu einem leichten Rückgang der Permafrosttemperaturen und zu einer deutlichen Abnahme der Blockgletschergeschwindigkeiten. In größerer Tiefe stiegen die Permafrosttemperaturen als Folge langfristiger Klimaentwicklung weiter an oder blieben stabil.

Résumé

Le réseau suisse d'observation du pergélisol PERMOS documente l'état et les changements du pergélisol dans les Alpes suisses sur la base de mesures de température du sol, de résistivité électrique et de vitesse des glaciers rocheux. Plus de 20 ans de données mettent en évidence une tendance générale au réchauffement et à la dégradation du pergélisol dans les Alpes suisses. Il existe également un degré de variabilité spatiale dû aux caractéristiques locales de chaque site ainsi qu'aux variations à court terme des conditions météorologiques.

La température moyenne annuelle de l'air au cours de l'année hydrologique 2022 (octobre 2021 à septembre 2022) a été supérieure d'environ 1,5 °C à la norme 1981-2010, faisant de 2022 la deuxième année hydrologique la plus chaude jamais mesurée en Suisse. En plus de températures de l'air supérieures à la moyenne pendant la majeure partie de l'année, l'année hydrologique 2022 a également été caractérisée par des hauteurs de neige inférieures à la moyenne durant l'hiver, en particulier dans le sud, et une disparition précoce de la couverture neigeuse.

En raison de ces conditions météorologiques, les températures moyennes annuelles à la surface du sol (MAGST) mesurées au cours de l'année hydrologique 2022 ont augmenté par rapport à l'année précédente à tous les sites et pour tous les types de terrains. Pour les sites constitués de matériaux meubles tels que les éboulis et les glaciers rocheux, la MAGST était supérieure d'environ 1 °C à celle de l'année hydrologique 2021. Les conditions plus chaudes à la surface du sol se sont traduites par des épaisseurs de couche active (ALT) plus importantes en 2022 qu'en 2021, avec de nouvelles valeurs record mesurées dans deux tiers des forages. Toutes les ALT enregistrées en 2022 étaient proches ou égales au maximum de la série de mesure. À 10 m de profondeur, la température moyenne annuelle du pergélisol observée en 2022 a diminué de quelques dixièmes de degré pour la majorité des sites. Cela constitue une réponse tardive aux basses températures de surface observées en 2021. À plus grande profondeur, c'est-à-dire à environ 20 m, les températures du pergélisol sont restées stables ou ont continué d'augmenter par rapport à l'année précédente. À certains sites, de nouvelles valeurs record ont même été atteintes.

Les résistivités électriques mesurées dans le pergélisol en 2022 ont diminué sur tous les sites de 1,5 à 20 %, atteignant dans certains cas des valeurs record. Cela indique une augmentation générale de la teneur en eau liquide du pergélisol, qui est considérée comme une conséquence directe de la fonte de la glace présente dans le sol.

Suite à la baisse des températures du pergélisol à une profondeur d'environ 10 m en 2022, les glaciers rocheux observés ont fortement décéléré avec une diminution moyenne de la vitesse de -34% par rapport à 2021 et une diminution maximale de -87% pour le glacier rocheux Yettes-Condjà en Valais. La vitesse mesurée à la surface des glaciers rocheux reflète indirectement l'évolution du régime thermique du pergélisol entre le toit du pergélisol et l'horizon de cisaillement : Lorsque les températures du pergélisol diminuent, les glaciers rocheux s'accélèrent généralement.

Dans l'ensemble, l'année hydrologique 2022 a été caractérisée par des conditions extrêmement chaudes à la surface et dans les premiers mètres du sol, entraînant des valeurs élevées ou records d'ALT et une diminution générale de la résistivité électrique du pergélisol. À 10 m de profondeur, l'effet à retardement des conditions froides observées près de la surface en 2021a entraîné une légère baisse des températures du pergélisol et une diminution marquée de la vitesse des glaciers rocheux. À plus grande profondeur les températures du pergélisol ont continué d'augmenter ou sont restées stables en réponse aux changement climatique à long-terme.

Riassunto

La Rete Svizzera di Monitoraggio del Permafrost PERMOS documenta lo stato e i cambiamenti del permafrost nelle Alpi svizzere attraverso numerose misure sul terreno delle temperature del suolo, resistività elettriche e velocità dei ghiacciai rocciosi. Oltre 20 anni di dati testimoniano una tendenza al riscaldamento e alla degradazione del permafrost nelle Alpi svizzere. Naturalmente, esistono anche variabilità spaziali legate alle caratteristiche locali dei diversi siti di studio e variazioni sul breve termine dovute alle condizioni meteorologiche.

La temperatura media annua dell'aria nell'anno idrologico 2022 (da ottobre 2021 a settembre 2022) è stata di circa 1.5 °C superiore alla media a lungo termine 1981–2010, rendendolo il secondo anno idrologico più caldo mai misurato in Svizzera. Le temperature dell'aria sono state superiori alla media per la maggior parte dell'anno e in inverno sono state misurate altezze della neve inferiori alla media, soprattutto al Sud delle Alpi. Il manto nevoso è scomparso prima del solito.

Come risultato di queste condizioni meteorologiche, la temperatura media annua della superficie del suolo (MAGST) dell'anno idrologico 2022 è aumentata per tutti i siti e forme geomorfologiche rispetto all'anno precedente. Nei siti con terreni sciolti, come falde di detrito e ghiacciai rocciosi, MAGST è stata superiore di circa 1 °C rispetto all'anno idrologico precedente (2021). Le condizioni più calde in superficie hanno portato, nel 2022, a un aumento dello spessore dello strato attivo (ALT) rispetto al 2021, con nuovi valori da record misurati per due terzi dei sondaggi profondi monitorati. Tutte le ALT registrate nel 2022 hanno raggiunto o si sono avvicinate al valore massimo della serie storica. A 10 m di profondità, la temperatura media annua del permafrost nel 2022 è diminuita di qualche decimo di °C per la maggior parte dei siti, il che è considerato una risposta ritardata alle temperature più basse della superficie del suolo osservate nel 2021. A profondità maggiori di 20 m, le temperature del permafrost sono rimaste stabili o hanno continuato ad aumentare rispetto all'anno precedente. In alcuni siti sono stati raggiunti nuovi valori record.

Le resistività elettriche del permafrost misurate nel 2022 sono diminuite in tutti i siti tra l'1.5 e il 20%, raggiungendo valori minimi da record in alcuni siti. Ciò indica un aumento generale del contenuto di acqua liquida all'interno del corpo del permafrost quale conseguenza diretta della degradazione del ghiaccio nel suolo.

Nel 2022, in seguito alla diminuzione delle temperature del permafrost a una profondità di circa 10 m, i ghiacciai rocciosi monitorati hanno subito una forte decelerazione, con una diminuzione media della velocità di –34% rispetto al 2021 e una diminuzione massima di –87% osservata ai Yettes-Condjà, in Vallese. La velocità di superficie dei ghiacciai rocciosi riflette indirettamente l'evoluzione del regime termico del permafrost tra il tetto del permafrost e l'orizzonte di taglio: quando le temperature del permafrost aumentano, i ghiacciai rocciosi generalmente accelerano.

Complessivamente, l'anno idrologico 2022 è stato caratterizzato da condizioni estremamente calde in superficie e nei primi metri di profondità del terreno, facendo registrare una profondità particolarmente marcata o da record di ALT e una generale diminuzione della resistività elettrica del permafrost. A 10 m di profondità, l'effetto ritardato delle condizioni fredde in prossimità della superficie del suolo osservate nel 2021 ha portato a una leggera diminuzione delle temperature del permafrost e a una marcata diminuzione delle velocità dei ghiacciai rocciosi. A profondità maggiori, in risposta a dinamiche climatiche di lungo termine, le temperature del permafrost hanno continuato ad aumentare o sono rimaste stabili.

Contents

1 Introduction

The Swiss Permafrost Monitoring Network (PERMOS, www.permos.ch) documents the state and changes of permafrost in the Swiss Alps based on field measurements of a selected set of variables. Results are published annually in the *Swiss Permafrost Bulletin*. The reporting is based on the hydrological year because of the significant influence of the snow cover and its timing on the permafrost conditions. This report covers the hydrological year 2022, which includes the period from 1 October 2021 to 30 September 2022.

Permafrost is an invisible thermal subsurface phenomenon and defined as ground material remaining at or below 0 °C for at least two consecutive years. Permafrost sensitively reacts to climatic changes and is one of the Essential Climate Variables (ECVs) defined by the Global Climate Observation System (GCOS) of the World Meteorological Organization (WMO). The three products associated to the ECV «Permafrost» are: i) permafrost temperature, ii) active layer thickness (ALT) and iii) rock glacier velocity (RGV, see WMO 2022). Internationally, permafrost is observed in the framework of the Global Terrestrial Network for Permafrost (GTN-P, Streletskiy et al. 2021).

The monitoring setup of PERMOS is based on in-situ measurements of three complementing variables, which is consistent with the requirements of the ECV «Permafrost» (WMO 2022): PERMOS collects time series of 1) ground temperatures at the surface (GST) and at depth in boreholes, 2) permafrost resistivities as a proxy for changes in ground ice content, and 3) rock glacier velocities. Active layer thickness (ALT) is derived from temperature time series measured at multiple depths in boreholes. In addition, meteorological data are obtained at selected sites, and mass movements (i.e., rock falls and rock avalanches) originating from permafrost areas are documented.

The site selection follows a landform-based approach because differences in the permafrost evolution related to varying topography, snow regimes, and ground ice contents are considered more important in a small country than those due to regional climate conditions (PERMOS 2019, Noetzli et al. 2021).

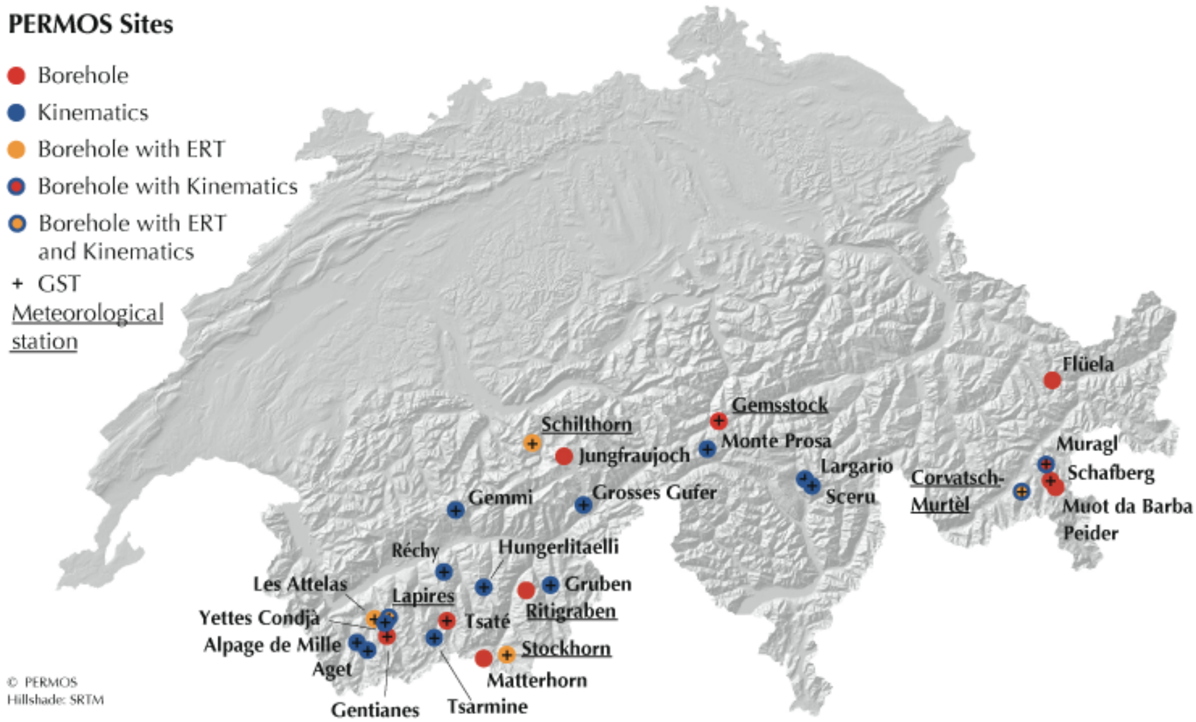

Figure 1.1: PERMOS field sites and measured variables in 2022.

In 2022, the PERMOS network included 27 field sites (Figure 1.1, Table A.1): Ground temperatures are measured at 15 sites in 27 boreholes (1–3 boreholes per site) of 14–100 m depth. Six of these sites are equipped with automatic weather stations (see Hoelzle et al. 2021) and for 5 sites, geophysical surveys are conducted annually along fixed installed profiles. RGV is measured by annual terrestrial surveys at 15 sites (with 1 to 2 rock glaciers) and 8 of these are equipped with a permanently installed GNSS devices. GST is measured at 22 PERMOS sites with a total of about 230 miniature data loggers.

PERMOS is financially supported by the Federal Office of Meteorology and Climatology MeteoSwiss in the framework of GCOS Switzerland, the Swiss Federal Office for the Environment (FOEN) and the Swiss Academy for Sciences (SCNAT). Seven academic partner institutions (ETH Zurich, Universities of Fribourg, Innsbruck, Lausanne and Zurich, University of Applied Sciences and Arts of Southern Switzerland, and WSL Institute for Snow and Avalanche Research SLF) are responsible for site maintenance and data collection. The PERMOS Office (UniFR and WSL-SLF) operates the network, implements the monitoring strategy, manages and analyses the data, and is in charge of publishing and communicating the results. Two standing committees advise and supervise the network, politically and financially (Steering Committee) as well as scientifically (Scientific Committee).

2 Weather and climate

Air temperature and snow height are the key meteorological variables influencing the seasonal and inter-annual variations of the permafrost thermal regime. Changes in air temperature drive changes at the ground surface in periods with little or no snow, and all year round for locations where no thick snow cover develops during winter (steep slopes or wind-blown ridges). The onset of an insulating snow cover and the time when the ground surface becomes snow free are highly relevant for permafrost evolution: An early snow cover conserves the summer heat in the ground while a long-lasting snow cover insulates the ground from increasing air temperatures in spring or early summer. The weather and climate information presented in this bulletin is based on MeteoSwiss (2022, 2023) and Pielmeier et al. (2022).

Winter 2022 was clearly warmer than the long-term mean 1981–2010, with average precipitation in the North of Switzerland and very dry and sunny conditions in the South. The first snow fall occurred during the first half of November at high elevations along the Alpine main ridge and in Grisons (Figure 2.1). While January was generally warm and dry, extensive snow fall occurred in February, except in the South. March was dry again with marked Sahara dust events, which later accelerated the snow melt. The long-awaited snow falls in the South only arrived at the end of April. The weather conditions in May were again extremely dry and mild. May 2022 was the warmest ever measured and the below-average snow cover at higher elevations melted quickly. Spring 2022 was the second warmest since the start of the measurements in 1864.

The very warm conditions continued in all regions for the remainder of the hydrological year 2022: three heat periods between mid-June and early August led to the second warmest summer on record, with 2.6 °C above the mean 1981–2010. Only Summer 2003 was warmer, with 3.6 °C above the norm. On 25 July 2022, a new record elevation of the 0 °C isotherm was registered at 5184 m asl. October 2022 was the warmest on record, with monthly means values of 3.2–4.7 °C above the mean 1981–2010. Autumn 2022 was the third warmest measured since 1864.

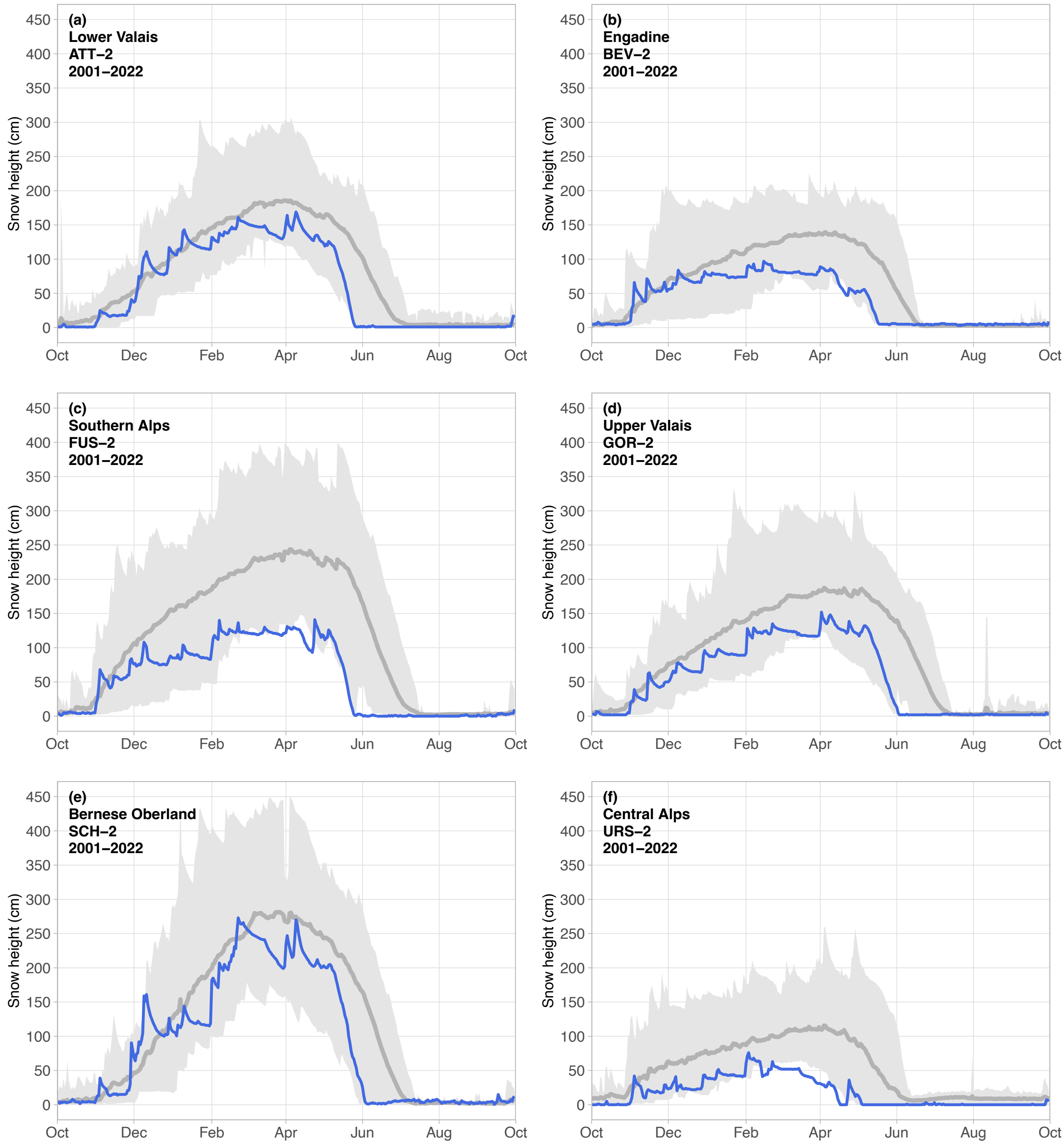

Figure 2.1: Snow height at six IMIS stations during winter 2022 (blue line) compared to the mean (thick grey line) and range (light grey shaded area) of the period 2001–2021. Data were corrected for outliers and aggregated to daily median values. The stations represent different regions in the Swiss Alps (below the region, the name of the IMIS station is given) : a) Lower Valais, b) Engadine, c) Southern Alps, d) Upper Valais, e) Bernese Oberland, and f) Central Alps. Data source: IMIS/SLF.

Overall, the hydrological year 2022 was characterized by a warm winter with below-average snow heights, an early snow melt and very warm conditions from spring to autumn. The mean annual air temperature (MAAT) was 1.5 °C higher than the 30-year average 1981–2010 (Figure 2.2). The hydrological year 2022 was the second warmest since the start of the measurements (the calendar year 2022 was even the warmest ever measured, with temperatures 2 °C above the mean 1981–2010).

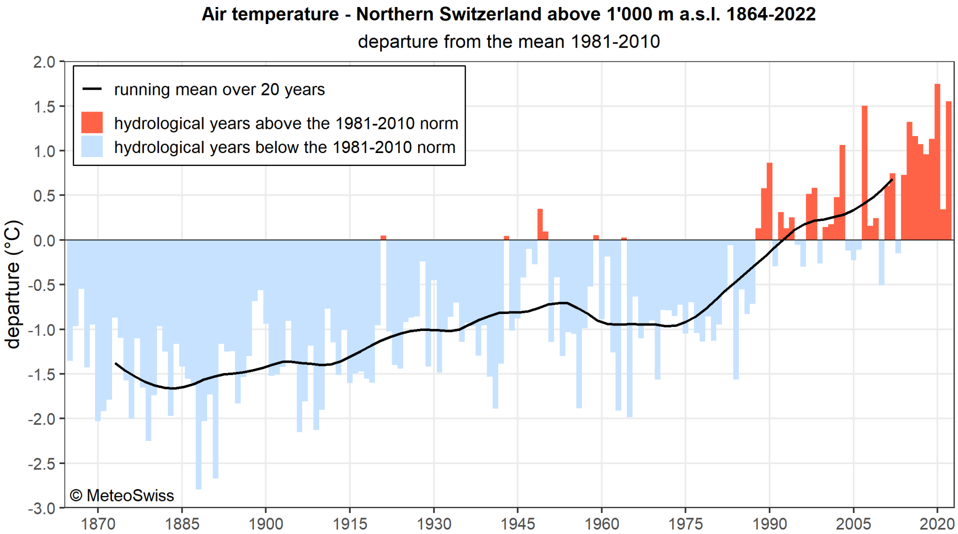

Figure 2.2: Air temperature deviation from the 1981–2010 norm based on homogenized data series for Swiss stations above 1000 m asl. Annual values refer to the hydrological year. Adapted from MeteoSwiss (2023).

3 Thermal state of permafrost

Ground temperatures are the only direct, quantitative and comparable observations of permafrost, and constitute the basis of climate-related monitoring of permafrost. Borehole measurements are further used to derive the ALT (Section 3.2), i.e., the thickness of the layer that freezes and thaws annually. The point information from boreholes is complemented by spatially distributed temperature measurements at the ground surface (Section 3.1).

3.1 Ground surface temperatures

Ground surface temperatures result from the energy balance at the ground surface. GST are continuously recorded at 22 sites with 5–15 miniature temperature data loggers each (236 in total in 2022). The data loggers are distributed close to boreholes or to geodetic survey points, at locations of varying topographic setting or ground surface characteristics. They are buried a few decimetres to shield them from direct solar radiation, which would cause warming of the casing. GST are recorded with a temporal resolution of 1–3 hours, depending on the device used. The measurements provide information on the thermal conditions at the ground surface and their spatial variability. GST changes subsequently penetrate to depth with increasing filtering and delay with depth.

For further analysis, individual GST time series are aggregated to daily mean values and gap-filled using the quantile mapping approach described by Staub et al. (2017). Only the most complete GST time series are selected: they cover at least 5 years, include the most recent year, and have values for 85% of the time after gap filling. Finally, site means are only calculated for the time periods with data available for all selected GST time series.

The mean annual ground surface temperature (MAGST) during the hydrological year 2022 was more than 1 °C higher than in the previous year for all the sites. It was between 0.5 to 1.5 °C above the decadal average 2006–2015 (Figure 3.1). At several sites, the mean GST of the hydrological year 2022 was the highest ever measured for the 1–2 decades of observation, beating previous record values from the hydrological years 2003, 2015 or 2020.

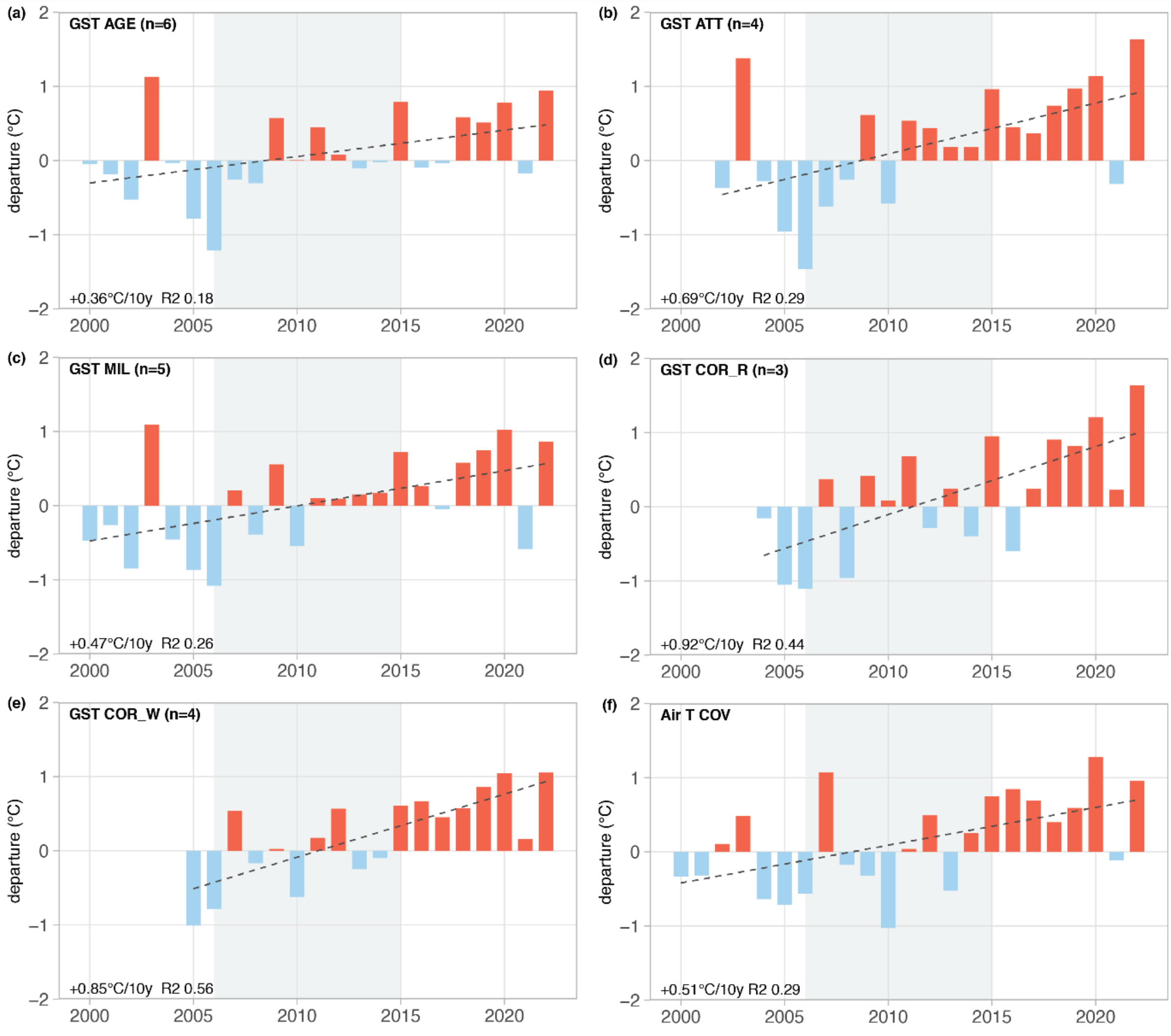

Figure 3.1: Departure of the mean annual ground surface temperature from the decadal average 2006–2015 (hydrological years) for two rock glacier sites in the Lower Valais, Aget (AGE, a) and Alpage de Mille (MIL, c), the Les Attelas talus slope (ATT, b) as well as flat (COR_R, d) and steep (COR_W, e) bedrock on Corvatsch in the Engadine. For comparison, the air temperature anomaly measured at Corvatsch is shown (COV, f, Data: MeteoSwiss). The number in brackets indicates the number of individual loggers used to calculate a site mean. The dashed line indicates the linear trend for the time series since the year 2000 (except for COR_W, where the time series starts in 2005).

The Ground Freezing Index (GFI, defined as the sum of the negative daily temperatures during a hydrological year) is both slightly higher and lower than in the previous year, depending on the site (Figures 3.2 and 3.3). The Ground Thawing Index (GTI, defined as the annual sum of positive daily temperatures) can only be determined for sites with data reaching until the end of September 2022. For these sites, GTI values are clearly higher than in the previous cooler summer, with new record values for all sites reflecting the extraordinarily warm conditions in summer 2022.

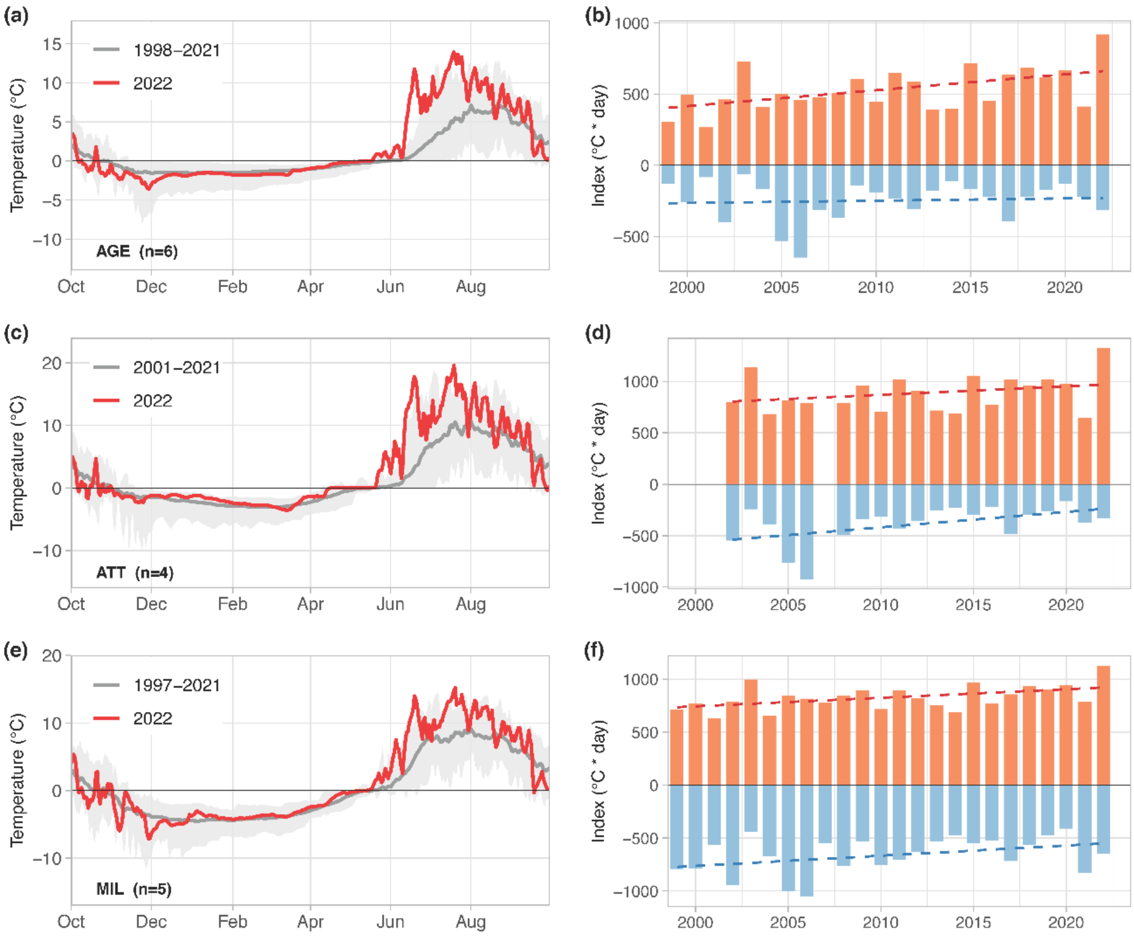

Figure 3.2: Left: Daily mean ground surface temperatures during the hydrological year 2022 (red lines) compared to the average of the previous ca. 20 years (grey lines). Right: Ground Freezing and Thawing Indices (GFI and GTI) in unconsolidated material (rock glacier Aget a-b, talus slope Les Attelas c-d, rock glacier Alpage de Mille e-f). The number of loggers (n) used in the site average is given in brackets in the left panels. Dotted lines in the right panels indicate the linear trend since the start of the measurements.

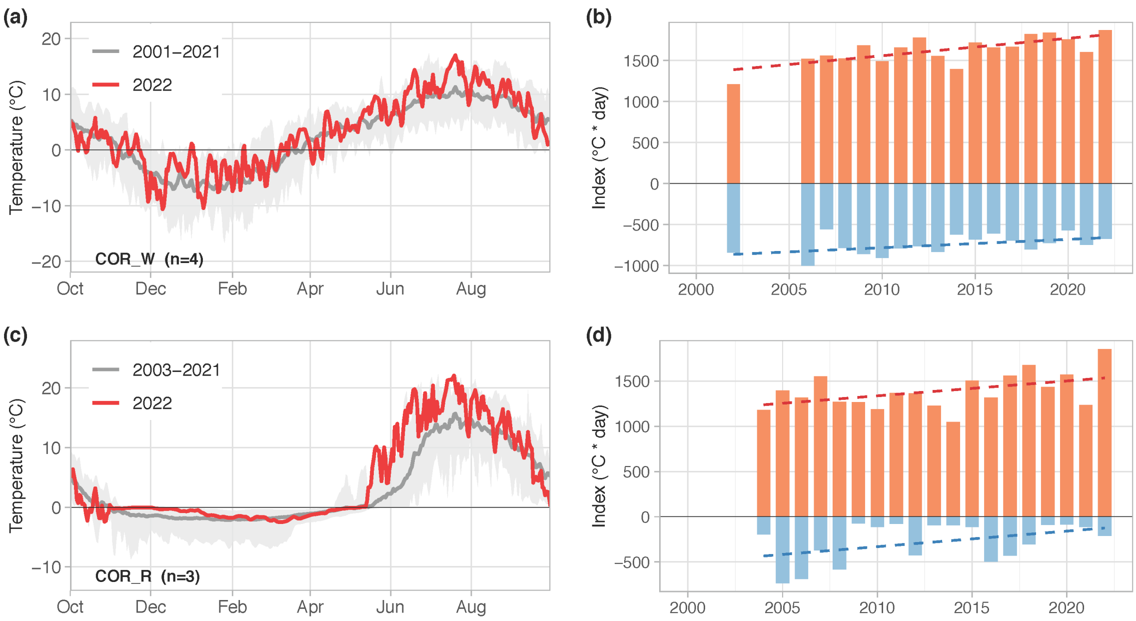

Figure 3.3: Same as Figure 3.3 for steep (top) and flat (bottom) bedrock on Corvatsch (GR).

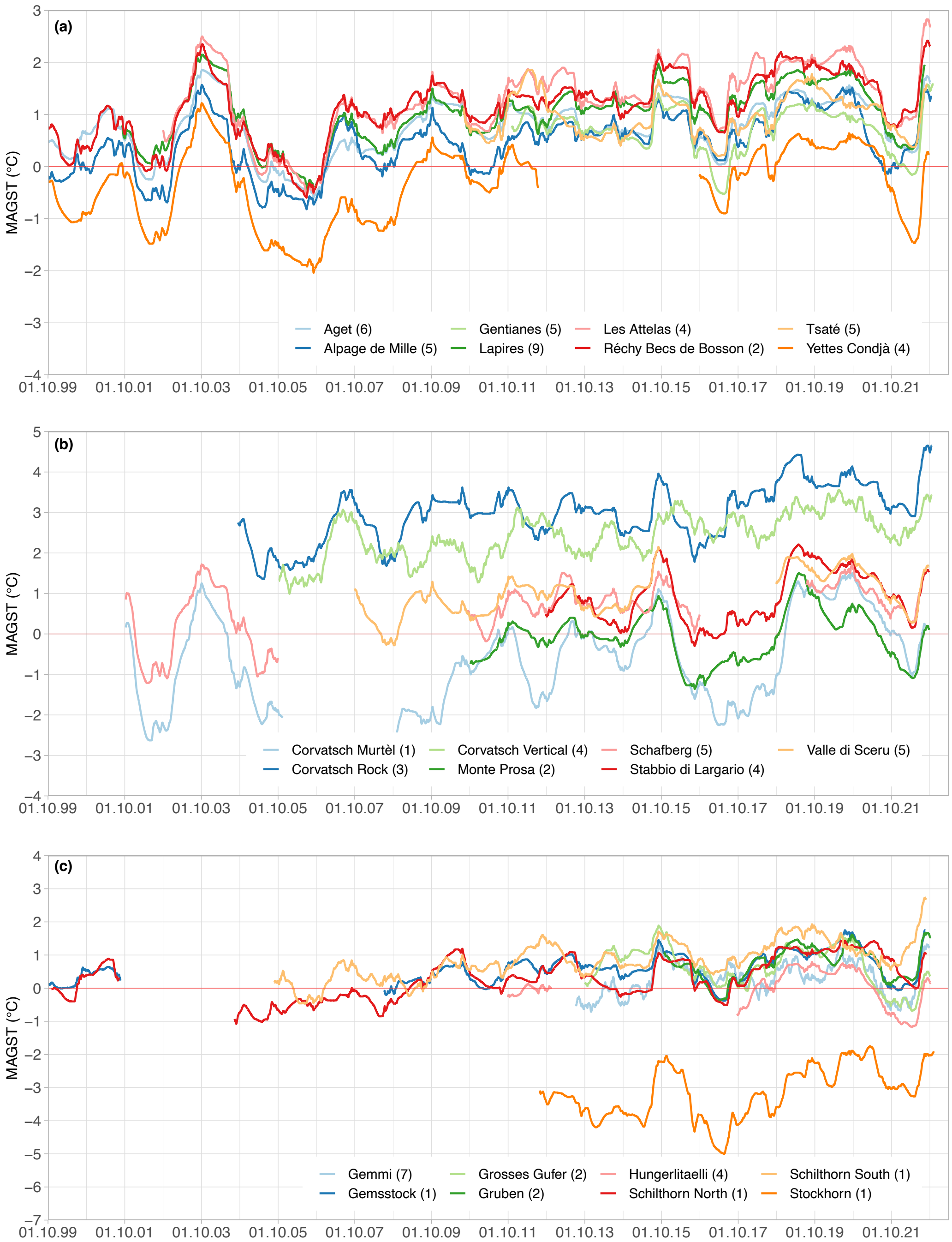

Figure 3.4: Running mean of the annual ground surface temperature (MAGST) for sites in the Lower Valais (a), the East and South of the Swiss Alps (b), as well as the Upper Valais and Northern Alps (c). Corvatsch Rock and Corvatsch Vertical are measured in flat and steep bedrock. All other sites are coarse blocky landforms (rock glaciers and talus slopes). Series depict running annual mean temperatures and site averages of several individual time series (the number of loggers used is given in brackets).

The long-term evolution of GST can be assessed using a running annual mean (rMAGST, Figure 3.4). During the previous year 2021, rMAGST significantly decreased at all PERMOS sites after it remained at high level for about four years. In the hydrological year 2022, rMAGST strongly increased again, and even reached new record levels for several regions at the end of the period.

The rMAGST has been above 0 °C at most of the sites since the start of the time series 1–2 decades ago (Figure 3.4). This points to the importance of the so-called thermal offset (e.g., Burn and Smith 1988, Hoelzle and Gruber 2008), which can cause the MAGST to be higher than the temperature at the top of the permafrost (i.e., the permafrost table): permafrost can exist in the subsurface despite positive MAGST. The thermal offset results from differences in thermal conductivity between frozen and thawed material, as well as from non-conductive heat transport in the active layer. In addition, the permafrost conditions at depth are not in thermal equilibrium with the current thermal conditions at the surface.

3.2 Active layer thickness

The maximum penetration depth of the 0 °C isotherm during summer/autumn defines the ALT. It reflects the snow and atmospheric conditions during the current and previous year. The ALT is calculated by linear interpolation of daily ground temperatures measured in boreholes using the lowermost sensor in the active layer (T>0°C) and the uppermost sensor in the permafrost (T≤0°C). Because freeze/thaw processes and varying ground characteristics in the uppermost meters can result in a non-linear temperature profile, quantitative changes in ALT should be interpreted with care. Qualitative changes and general trends in ALT are however considered to be robust.

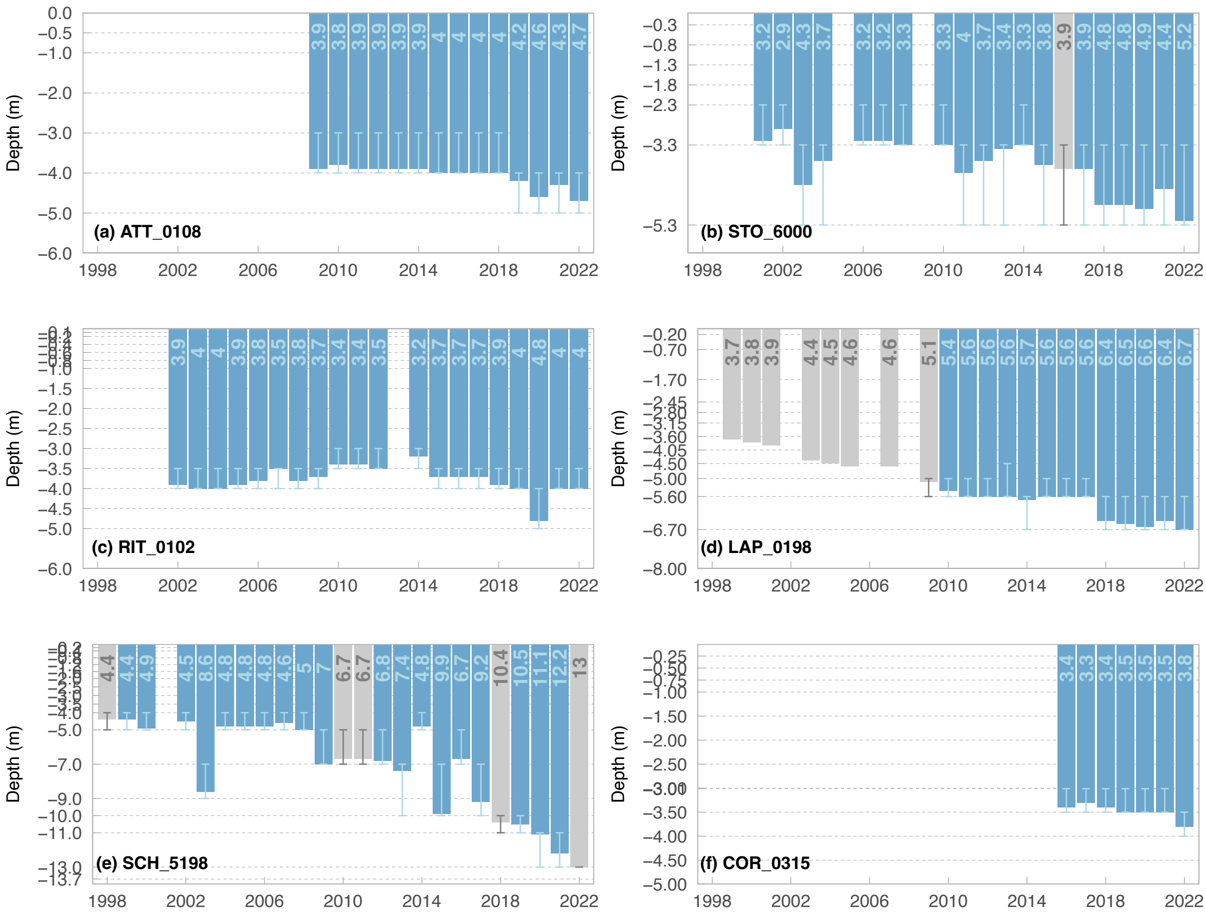

Figure 3.5: Active layer thickness (ALT) derived from borehole temperature data measured in the Attelas talus slope (a), on the Stockhorn Plateau (b), in the Ritigraben rock glacier (c), in the talus slope at Lapires (d), on the summit crest of Schilthorn (e) and in the borehole in rock glacier Murtèl-Corvatsch from 2015 (f). The uncertainty bars are defined by the thermistors used for the interpolation of the ALT. Grey colors indicate an estimated ALT due to data gaps or questionable data quality.

The ALT in 2022 could be determined for 12 boreholes at 7 sites. For two boreholes at two sites, a first estimate could be made (ATT_0208, FLU_0102). For 6 boreholes at 3 sites, no data for autumn 2022 are available yet (MBP, SBE, MAT). For 7 boreholes, the calculation of an ALT is not possible due to the either no permafrost (MUR_0199, GEM_0106), broken sensors at the relevant depths (COR_0287, MUR_0299), no sensors in the active layer (JUN_0190), or the active layer reaching deeper than the lowest available sensor (SCH_5198, MUR_0499).

ALT calculated for the hydrological year 2022 were between 2.9 m (Flüela, FLU_0102) and >13 m (Schilthorn, SCH_5198, Figure 3.5). The ALT reached a new record for 7 boreholes at 6 sites. However, all previous records were observed during the past 2 years and all ALT values for 2022 are close to these record values. The largest increase compared to the year 2021 was observed at the Schilthorn borehole SCH_5318 and was more than 2 m. An increase of more than 1 m was observed at Stockhorn (STO_6100) and Tsaté (TSA_0117). At Lapires (LAP_1208) and Gentianes (GEN_0102), the ALT was 80 cm thinner than in 2021. For SCH_5198, the active layer has reached a new absolute maximum: the 0 °C isotherm reached further down than the lowest sensor at 13 m. At this depth, the temperature rose above 0 °C on 1 February 2023 (0.01 °C, Figure 3.6).

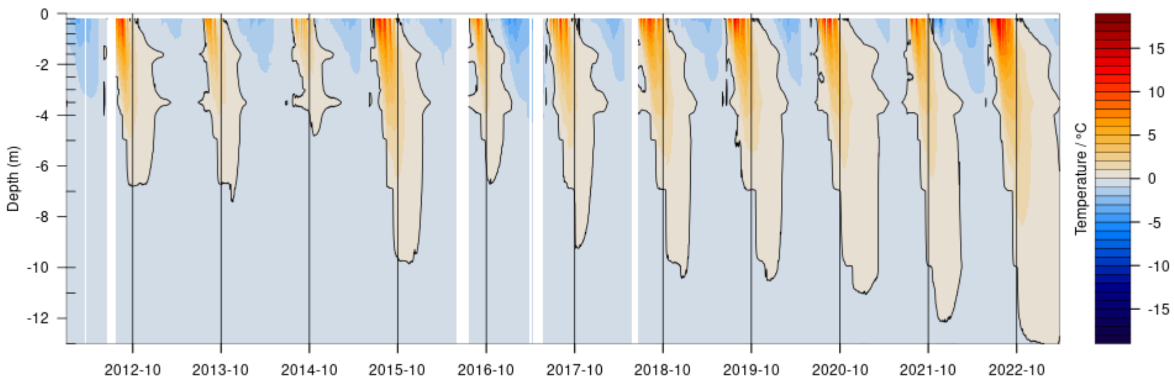

Figure 3.6: Contour plot of the ground temperatures measured in the shallow borehole on Schilthorn (SCH_5198) since 2012, where the 0 °C isotherm (black curve) reached a depth of 13 m (lowest sensor in the borehole) for the first time in February 2023.

3.3 Permafrost temperatures

Ground temperatures in the uppermost metres react to short-term variations in meteorological conditions. These variations are increasingly filtered and delayed with increasing depth. The signal delay is about half a year at 10 m depth. Seasonal variations can be measured down to the depth of the zero annual amplitude (DZAA), which is typically at 15–20 m in the permafrost in the Swiss Alps. Below the DZAA, ground temperatures react with considerable delay (years to decades) to multi-annual trends from atmospheric conditions, and their variation reflects climate-related changes. In addition to air temperature, the most important factors influencing permafrost temperature evolution are the timing of the winter snow cover (see Chapter 2) and the ground ice content (Chapter 4). When temperatures approach 0 °C in permafrost with a high ground ice content, temperature changes become minimal because of latent heat uptake during ice melt. To observe changes in the permafrost until the frozen material has thawed entirely, additional measurements sensitive to changes in ground ice and liquid water content are needed (see Chapter 4).

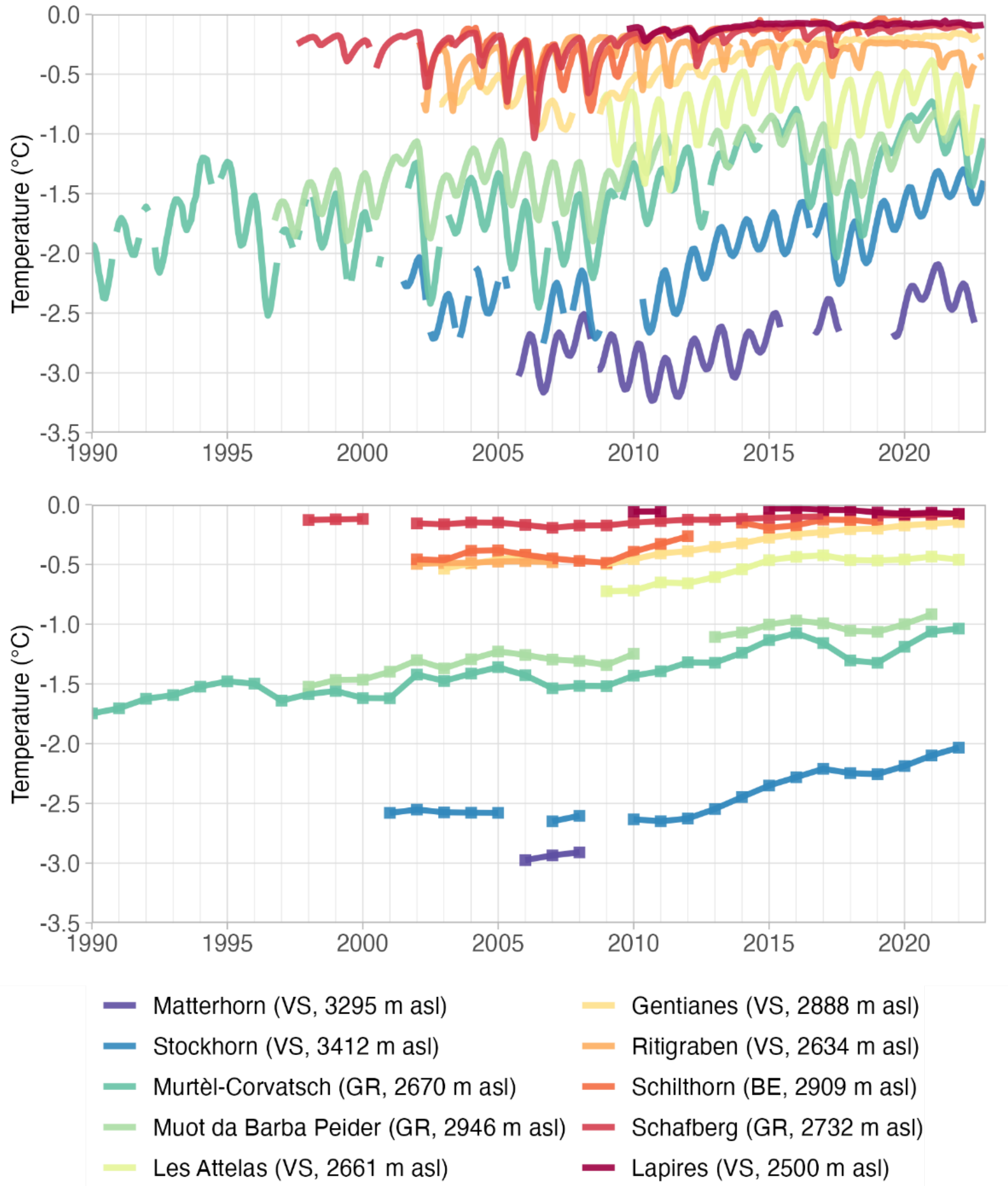

Figure 3.7: Permafrost temperatures measured in selected boreholes at 10 m (top, monthly means) and 20 m depth (bottom, means over the hydrological year).

Continuous permafrost temperatures are recorded at multiple depths in 27 boreholes at 15 sites (see Appendix, Table A.1). The boreholes are instrumented with multi-sensor cables and automatic logging systems, and many of them with remote access to the data. The recording interval varies between 1 and 24 h, depending on the instrumentation. Best practices for long-term borehole temperature measurements in mountain permafrost based on the experience of PERMOS are described by Noetzli et al. (2021). Borehole data are quality-checked for outliers. Further inconsistencies such as noise, jumps or sensor drift are detected based on visual inspection and plausibility (i.e., consistency with neighbouring data). The time series are aggregated to daily, monthly and annual mean values using depth-dependent criteria for data completeness.

During the hydrological year 2022, the mean annual permafrost temperatures at 10 m depth decreased by a few tenth of degree compared to the previous year for the majority of the PERMOS borehole sites (Figure 3.7). This decrease is interpreted as the result of the cooler conditions during the hydrological year 2021 and the delayed response of the ground temperatures to the thermal conditions at the ground surface by about half a year. A small increase (by a few hundredths of °C only) was observed at Schilthorn, Gentianes, Flüela, and Tstaté. Overall, nearly all borehole temperature time series are at a very high level compared to the entire time series and nearly all boreholes recorded their maximum temperature value at 10 m depth in the past 3 years.

A similar picture is observed for permafrost temperatures measured at depths of around 20 m, where they react to longer-term trends: Permafrost temperatures are at or close to the maximum recorded in the past 10–20 years. For several boreholes the mean annual temperature of the hydrological year 2022 at 20 m depth was the highest ever measured (e.g. ATT 0208, LAP_1108, LAP_1208, COR_0287, GEN_0102, SCH_5200).

4 Electrical resistivities

Electrical Resistivity Tomography (ERT) exploits the different electrical properties of the subsurface components. This method can accurately distinguish frozen from unfrozen terrains and is particularly sensitive to the presence of liquid water in the subsurface. By repeating ERT surveys with the exact same measurement setup (profile location and geometry) changes in the subsurface properties and more specifically changes in the liquid water, and ice content can be observed. Decreasing electrical resistivities indicate an increase of the ratio between liquid water and ice content, usually synonymous of overall ground ice melt. Conversely, increasing electrical resistivities indicate an increase of the ground ice content and/or a decrease in liquid water content.

Within PERMOS, electrical resistivities are measured at five borehole sites along profiles of 55 to 220 m length. The typical ERT monitoring installation includes cables connecting 48–55 permanently installed electrodes (stainless steel rods) to a water-proof connection box (see Figure 4.1), where the measurement device can be punctually or permanently connected. Measurements are performed once a year at the end of summer. Measured resistivities are quality controlled and inverted following the procedure described in Mollaret et al. (2019).

Figure 4.1: Electrical Resistivity Tomography (ERT) monitoring installation in August 2022 at Murtèl-Corvatsch (GR). Photo: C. Mollaret.

The electrical resistivities measured at the PERMOS sites span over several orders of magnitudes (lowest at Schilthorn ~3'000 Ωm, Figure 4.2a, and highest at Murtèl-Corvatsch ~300'000 Ωm, Figure 4.2e). To facilitate inter-site comparison and the analysis of the temporal evolution, spatially averaged resistivity values are computed for manually selected zones within the ERT tomograms (cf. Figure 4.2). These zones are delineated to encompass the largest possible homogeneous part of the permafrost (based on temperature and resistivity) and the part of the tomogram with the highest measurement density and quality (i.e., centre of the profile and not too deep). With this delineation, the zones are considered to be representative for the monitored site. The active layer is excluded where possible to focus on the permafrost and longer-term temporal variations.

Since the start of the observations, the electrical resistivities measured within the permafrost layer generally decreased at all sites (Figure 4.3). This trend is consistent with the reported increase in ALT and permafrost temperatures (see Chapter 3). It confirms a general increase in liquid water content within the permafrost layer, which is considered a direct consequence of ground ice degradation.

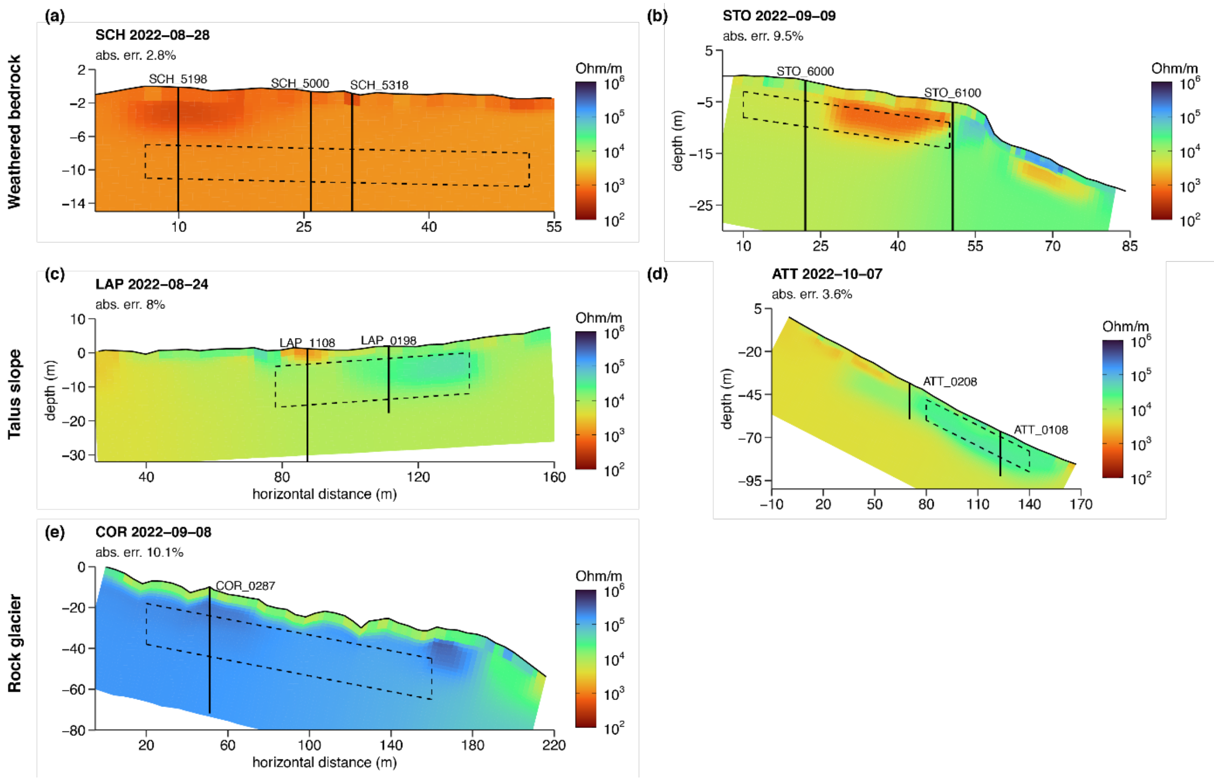

Figure 4.2: Electrical Resistivity Tomograms showing the resistivity distribution in 2022 at two bedrock sites (Schilthorn, a and Stockhorn, b), two talus slopes (Lapires, c and Les Attelas, d) and one rock glacier (Murtèl-Corvatsch, e). The representative zones used for the time series in Figure 4.3 are indicated with dashed boxes and the borehole positions are indicated with vertical black lines.

In 2022, resistivities decreased at all sites compared to 2021. The largest decrease of –20 % compared to 2021 was measured at Stockhorn (STO), whereas comparatively small decreases were observed at Les Attelas (ATT, –1.5%), Lapires (LAP, –4.5%) and Schilthorn (SCH, –3.8%). At Murtèl-Corvatsch (COR) the comparatively low data quality in 2020 and 2021 does not allow to analyse the recent evolution of resistivities. However, an overall decrease is observed between 2019 and 2022.

These results are consistent with the thermal conditions in 2022 (see Chapter 3) as well as with the sub-surface properties and topographical settings of the different sites. The largest resistivity decrease is observed at Stockhorn, a bedrock site with comparatively low ice content, where ground temperatures are mostly controlled by conductive heat transport. This decrease is consistent with the active layer deepening observed in summer 2022 as well as the record high permafrost temperatures at 20m depth.

The smallest resistivity decreases are observed at Les Attelas and Lapires, two talus slopes with considerably higher ice content, where conductive heat transport is less efficient and heat convection/advection via ventilation can take place. This is consistent with the comparatively small active layer deepening and small thermal response of the permafrost following the exceptionally warm summer 2022. At Schilthorn, the comparatively small resistivity decrease observed in 2022 is not in line with the observed record active layer thickness (>13 m) and record high permafrost temperatures at 20 m depth. The zone selected at Schilthorn is located within the active layer (still frozen at the time of the ERT survey) and is characterized by extremely low ice content, temperature close to 0 °C and low absolute permafrost resistivity. The observed resistivity response is thus likely due to inter-annual temperature changes rather than to changes in ground ice content. Overall, the changes of permafrost resistivity observed in 2022 are consistent with the evolution of permafrost temperatures and confirm a warming and degradation of the permafrost conditions in the Swiss Alps.

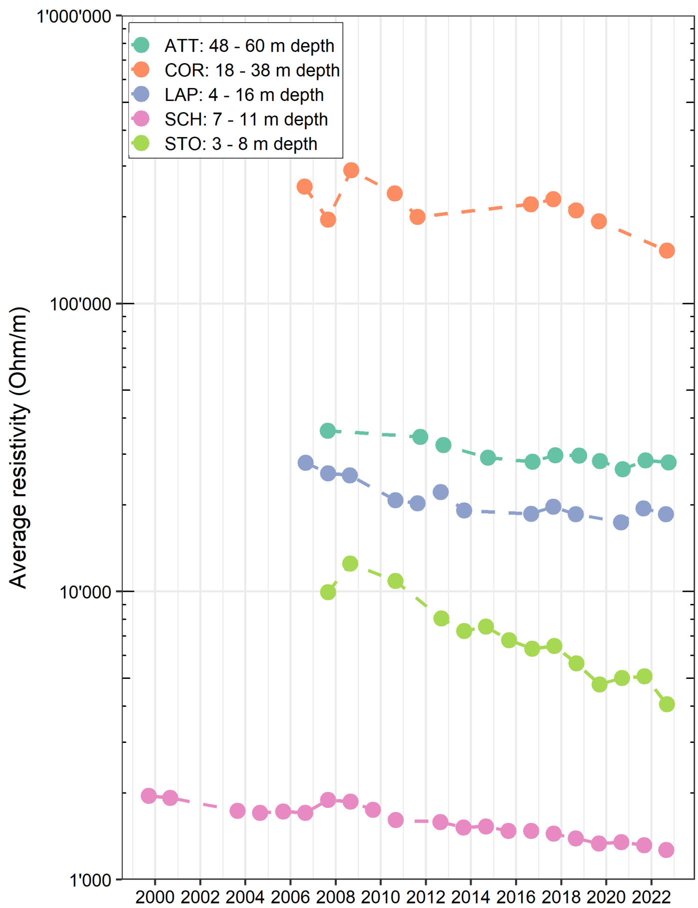

Figure 4.3: Average electrical resistivities of the permafrost zone (see Figure 4.2) at the end of summer for the 5 ERT sites in the PERMOS Network.

5 Kinematics

The kinematics of creeping permafrost landforms such as rock glaciers is primarily controlled by their intrinsic characteristics (e.g., internal structure and composition, topographical and geological settings), whereas changes over time are mainly driven by climate-sensitive processes. Inter-annual changes in rock glacier velocity are mostly related to the evolution of ground temperature and liquid water content between the upper surface of the permafrost (i.e., the permafrost table) and the layer at depth where most of the deformation occurs, the so-called shear horizon (Cicoira et al. 2020). Rock glacier surface velocities were shown to follow an exponential relation with air and ground surface temperature (i.e., increasing air/ground temperatures lead to an increase in velocity, see Staub et al. 2016, Frauenfelder et al. 2003).

Surface velocities of rock glaciers are measured by annual terrestrial geodetic surveys (TGS, Figure 5.1) at the end of summer (August-October), as well as by permanently installed GNSS devices (Figure 5.4). These two complementary methods allow to capture the seasonal velocity variations (permanent GNSS) as well as their spatially distributed annual and inter-annual changes (TGS).

Figure 5.1. GPS measurements on the Gemmi rock glacier. Photo: C. Pellet.

5.1 Annual rock glacier velocity

Annual TGS are performed using high precision differential GNSS or total stations. The positions of selected boulders (10–100 points per site covering the entire landform and stable areas nearby) are measured and used to calculate the surface velocity. Control points (i.e., points located on non-moving areas) are used calibrate and adjust the measured coordinates with an average accuracy in the range of mm to cm. A set of reference points is defined amongst the monitored boulders for each monitored rock glacier based on their spatial distribution (i.e., located within area of the rock glacier where surface displacements are dominantly related to permafrost creep) and data quality and completeness. These points are used to compute site averages (Figures 5.2 and 5.3).

The hydrological year 2022 was characterized by a marked overall velocity decrease: the mean of all sites decreased by –34% compared to 2021. The maximum decrease was observed at Yettes-Condjà (YET2, –87%) located in the Lower Valais region, which also exhibit the largest regional-average decrease (–57%, see Figure 5.2a). The minimum velocity decrease was observed at Muragl (MUR, 0%) in the Engadine (region average –8%, Figure 5.2d). In average, rock glacier velocity in the upper Valais region decreased by –16% in 2022 and by –49% in the Central/Southern Alps region.

The observed velocity decrease is consistent with the lower permafrost temperatures observed at 10 m depth, which reflect the colder year 2021 (see Chapter 3). The dry and warm conditions observed in winter, spring and summer 2022 affected the hydro-geological conditions at all sites, reducing the amount of liquid water present in the subsurface, thereby likely further contributing to the velocity decrease.

Overall, a coherent regional evolution of rock glacier velocity can be observed in the Swiss Alps, despite variable size, morphology and velocity range (Figure 5.3a). Since 2000, velocities have generally increased with marked inter-annual variability (velocity decrease observed in 2004–2006 and 2016–2018) due to varying meteorological conditions. Observed rates of increase are largest since 2010 and maximum velocities were recorded in 2015 and/or 2020 depending on the site. Over the last two years (2021 and 2022), rock glacier surface velocities have decreased which contrasts with the general increase observed since the start of the measurements.

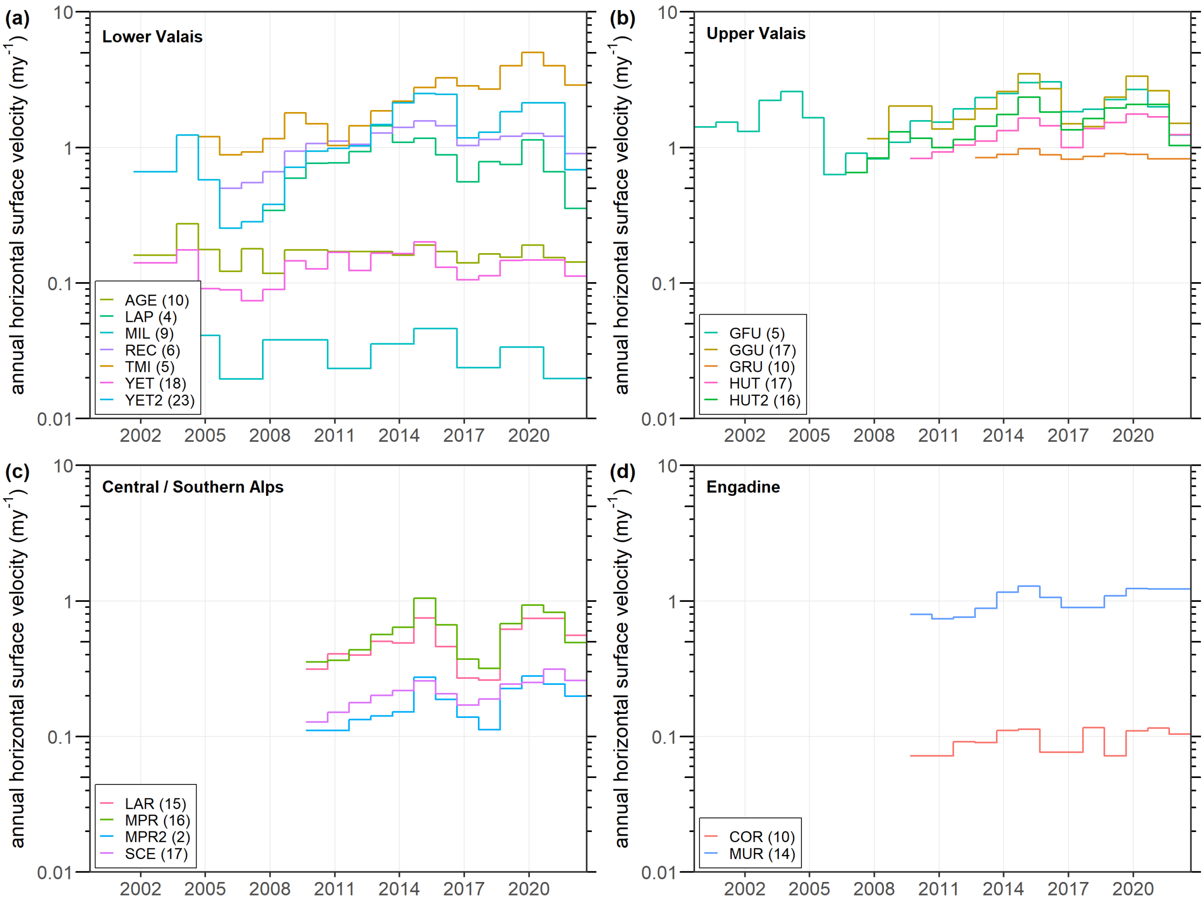

Figure 5.2: Pattern of horizontal surface velocity of 18 rock glacier lobes in the Swiss Alps, divided into four topo-climatic regions indicated in bold script. The number of reference points for each site is indicated in brackets. The abbreviations for the site names can be found in Table A.1.

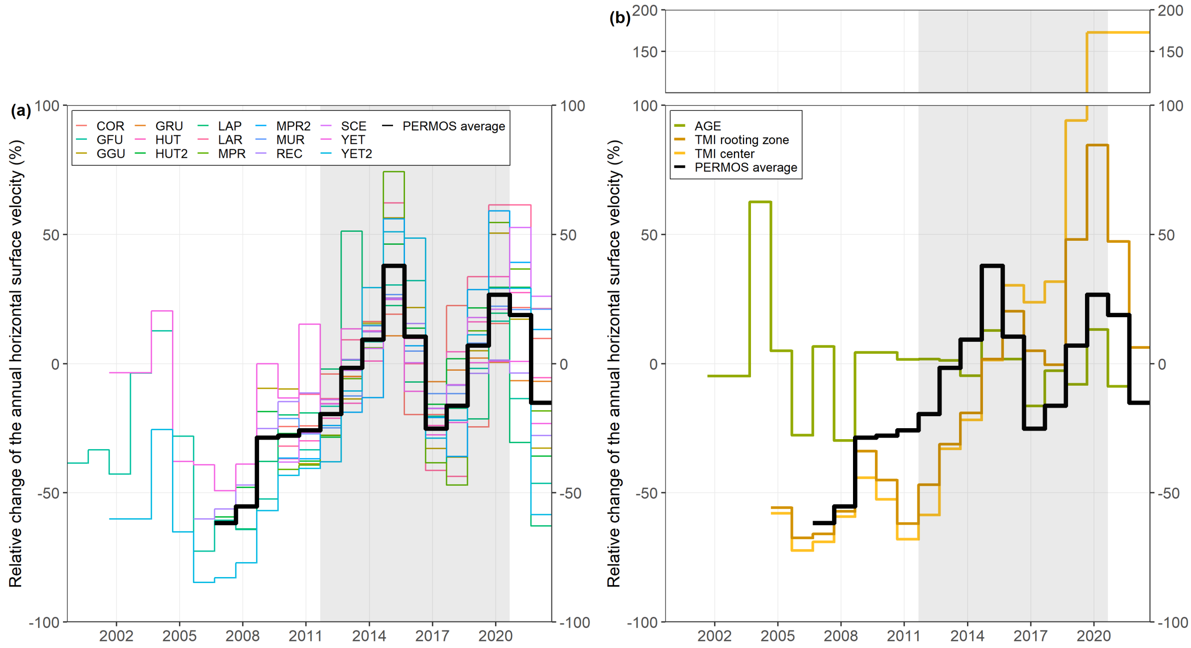

Figure 5.3: Mean annual horizontal surface velocity derived from terrestrial geodetic surveys relative to the reference period 2011–2020 (grey area). The black line represents the average of the Swiss Alps (excluding Tsarmine (TMI) and Aget (AGE)). (a) 15 monitored rock glacier lobes (for site abbreviations see Table A.1). (b)Two atypical rock glaciers (TMI divided into two areas).

Amongst the sites monitored in the framework of PERMOS, two rock glaciers do not follow this general pattern. Since 2015, rock glacier Tsarmine (TMI, Figure 5.3b) is accelerating more strongly especially in the central part and rock glacier Aget (AGE) is showing a decelerating trend since the start of the measurements (Figures 5.3b). These different kinematic behaviours are also a response to ongoing climate warming. A decelerating trend typically indicates in-situ permafrost degradation (i.e., ground ice loss), whereas an exceptional acceleration indicates ongoing destabilization (see Roer et al. 2008). In both cases, local factors (slope, hydrology, geometry, debris loading, etc.) become dominant and the inter-annual variations in rock glacier velocity are no longer predominantly driven by the climate. In the case of Tsarmine, the surface velocities started to exhibit diverging behaviour in 2016 between the upper (rooting zone) and lower (centre) part of the rock glacier. While the upper part is moving fast but nevertheless similarly to the inter-annual evolution of the swiss average, the lower part displayed marked and continuous acceleration since 2016 (Figure 5.3b upper panel). Scarps developed at the limit between the two different kinematic units due to the different velocity evolution.

5.2 Seasonal rock glacier velocity

Within the PERMOS network, permanent GNSS devices installed on 8 rock glaciers deliver continuous position measurements. The initial raw GNSS data are post-processed using a double-difference processing scheme to obtain robust quality controlled daily positions (see Cicoira et al. 2022). The high temporal resolution provided by permanent GNSS device enables the computation of monthly to daily displacements (depending on the absolute velocity of the rock glacier), which complement the annual TGS data (see section 5.1). Small velocity variations (smaller than +/-0.1–0.2 my^{-1}) have to be interpreted with caution as they can depend on a wide range of factors (e.g., snow pressure on the GNSS mast in winter, stability of the boulder in the terrain) and may not be representative of the general rock glacier motion (e.g., Wirz et al. 2014). To ensure the reliability of velocity observations and filter-out such short-term variations, positions are filtered and aggregated using a 30-days moving window.

Figure 5.4 shows the seasonal evolution of surface velocities of three rock glaciers: Gemmi (GFU, Upper Valais), Grosses Gufer (GGU, Upper Valais) and Monte Prosa (MPR, Central Alps). A typical seasonal pattern can be observed at all three sites: (i) decreasing velocities in winter with minima reached in April followed by (ii) a strong acceleration at the beginning of summer (during snow melt) and (ii) peak velocities observed at the end of summer (when near surface ground temperatures are the warmest). The amplitude of the seasonal variations is highly variable and is controlled by site-specific conditions (e.g. topography, geology, hydrology) as well as the specific meteorological and snow conditions.

At Gemmi and Grosses Gufer, the velocity throughout the hydrological year 2022 follows the typical seasonal pattern with two notable specificities. Firstly, the winter velocity minimum reached in April 2022 was the lowest velocity measured since 2017 at both sites. These low velocities result from pronounced velocity decreases observed during two consecutive years. Secondly, the acceleration following the snow melt in April was the least marked since 2017, which is consistent with the below average snow height observed in the entire Swiss Alps (see Chapter 2). At Gemmi, the end of summer velocity maxima exceeds the one reached after the snowmelt period for the first time since the start of the observations in 2017. This is consistent with the extreme high near surface ground temperatures recorded in summer 2022. At Monte Prosa, technical issues stopped data collection in October 2021, thereby preventing the analysis of recent seasonal velocity evolution at this site.

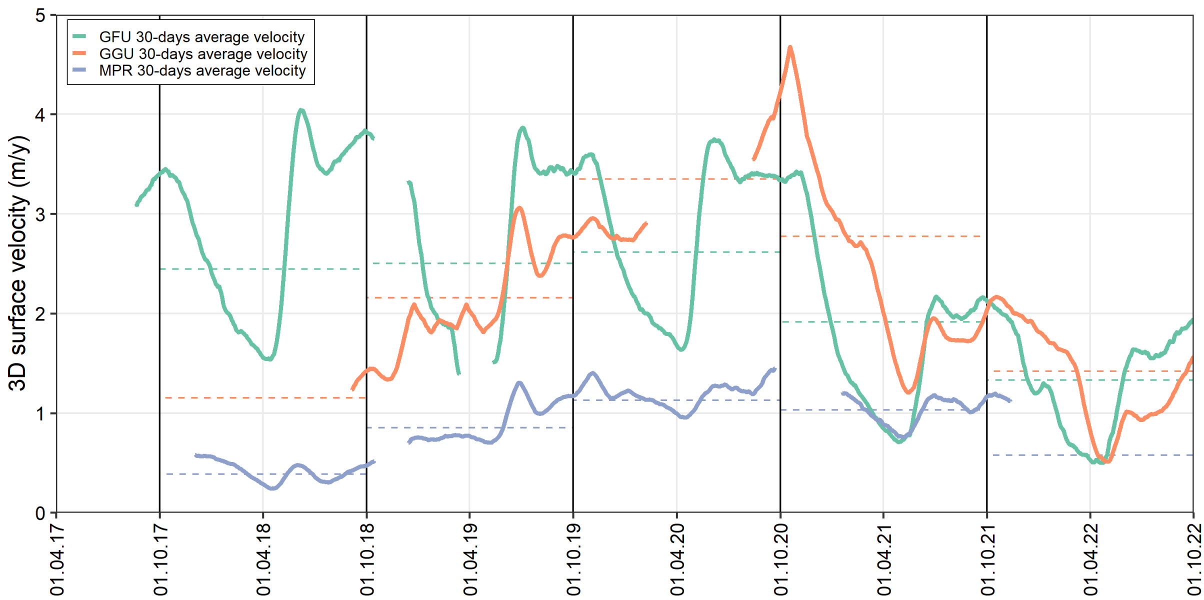

Figure 5.4: Evolution of the seasonal 3D surface velocity at the Gemmi (green), Grosses Gufer (orange) and Monte Prosa (blue) rock glaciers. The velocities are computed over 30-days periods. The dotted lines represent the annual surface velocity measured by TGS at the nearest boulder.

6 Conclusions

The Swiss Permafrost Monitoring Network PERMOS documents the state and changes of permafrost in the Swiss Alps based on field measurements of ground temperatures, electrical resistivities and rock glacier velocities. All observations show a consistent trend of continued warming and degradation of permafrost in the Swiss Alps since the start of the measurements. This general trend is marked by inter-annual variations in response to annual meteorological conditions, particularly the snow conditions and summer air temperatures.

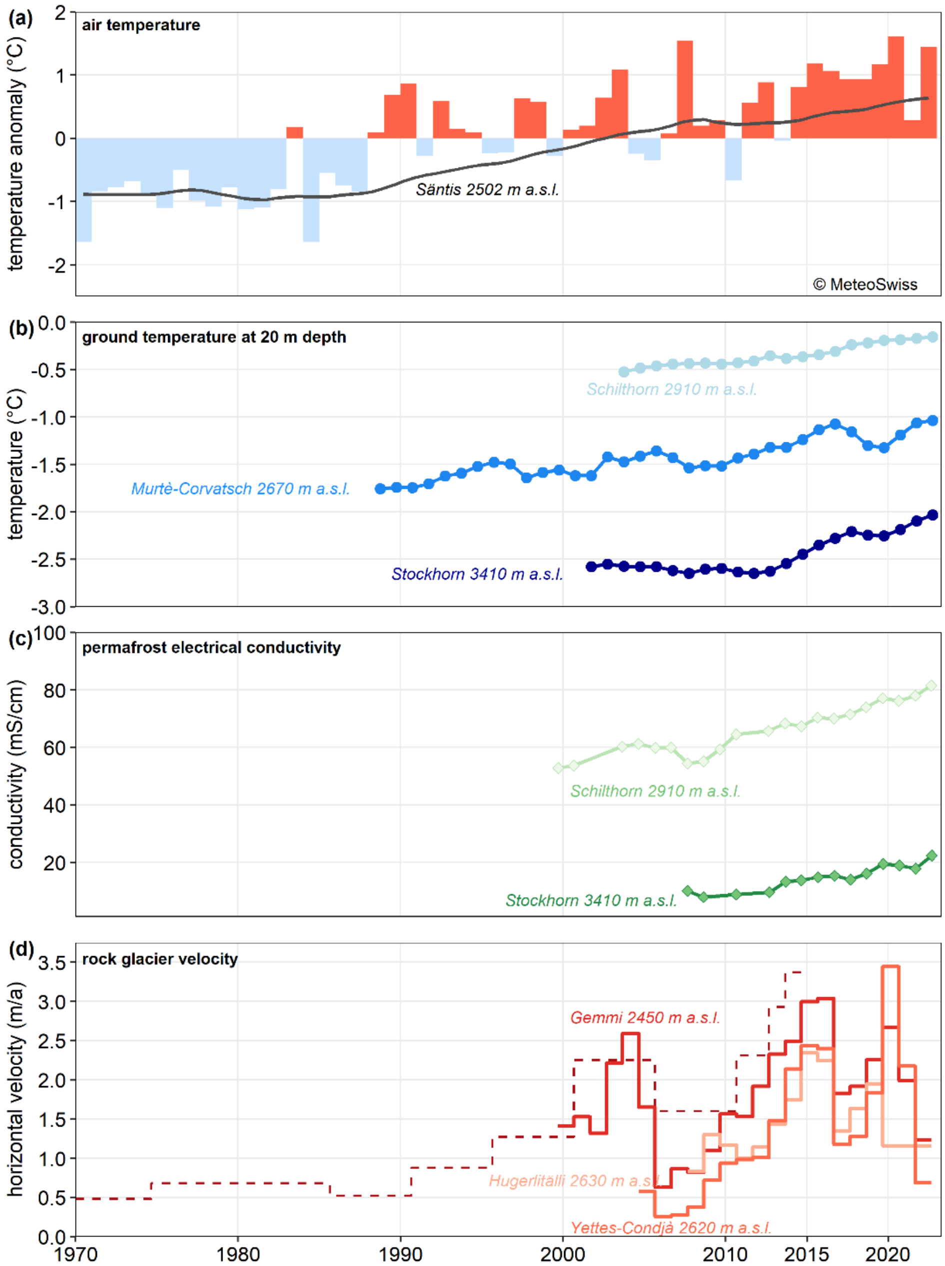

Figure 6.1: Evolution of the three observation elements of PERMOS: annual mean permafrost temperatures at 20 m depth (b), permafrost electrical conductivity (c), and rock glacier creep velocity (d). The dashed red line represents the horizontal surface velocity for Gemmi and is obtained by aerial photogrammetry. The data are compared to long-term air temperature data by MeteoSwiss (a).

The air temperature during the hydrological year 2022 was 1.5°C above the long-term mean 1981–2010. The year 2022 was the second warmest hydrological year (and the warmest ever calendar year) since the start of the measurements in 1864. It was characterized by a warm winter with below average snow heights and early snow melt followed by the second warmest summer on record and the third warmest autumn. The weather and climate conditions lead to the following permafrost conditions in the Swiss Alps during the hydrological year 2022 (Figure 6.1):

- Compared to previous years, ground surface temperatures were extremely high in 2022 and reached maximum values at several sites. This was a consequence of the extremely warm atmospheric conditions in summer/autumn 2022 and the early snow melt in spring.
- ALT observed in 2022 were overall greater than in 2021, with record thicknesses reached at 9 of the 15 sites. The largest ever ALT of more than 13 m was recorded at Schilthorn in February 2023.
- The permafrost temperatures measured at 10 m depth were under the delayed influence of the lower GST observed in 2021. This resulted in a slight decrease or stable temperatures in 2022. Permafrost temperature at 10 m have not (yet) been affected by the extreme warm 2022 conditions at the surface. At 20 m depth and at all sites, permafrost temperatures remained stable or continued to increase compared to the previous year. At some sites, new record values have even been reached.
- Permafrost electrical resistivities decreased at all sites compared to 2021. The talus slope sites exhibited the smallest resistivity decrease, due to lower efficiency of conductive heat transport in such coarse blocky terrains. The largest resistivity decrease was observed at the bedrock site Stockhorn with –20% compared to 2021.
- Compared to 2021, an overall marked decrease of rock glacier velocity was measured (Swiss average –34%, maximum recorded –87%). The signal is regionally variable, with larger decreases observed in the Lower Valais and Central/Southern Alps regions and smaller decreases in the Upper Valais and Engadine regions.

Overall, the permafrost conditions during the hydrological year 2022 were characterized by extremely warm conditions at the surface and in the uppermost metres, colder temperatures in the upper permafrost (low permafrost temperature at 10 m depth and lower creep velocities) and a continued increase of the permafrost temperatures at larger depth. The latter reflect the delayed thermal response of permafrost conditions to atmospheric forcing and do not yet react to the extreme summer 2022.

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Appendix

Table A.1: Location and characteristics of the PERMOS sites

Name	PERMOS Abbreviation	Regions	Morphology	X CH1903	Y CH1903	Elevation (m a.s.l.)	BHT	GST	ERT	TGS	GNSS	Meteo
Aget	AGE	Lower Valais	rock glacier	584500	95300	2900		X		X		
Les Attelas	ATT	Lower Valais	talus slope	587250	105000	2800	X	X	X			
Flüela	FLU	Engadine	talus slope, rock glacier	791500	180474	2501	X					
Gemsstock	GEM	Urner Alps	crest	689781	161789	2950	X	X				X
Gentianes	GEN	Lower Valais	moraine	589467	103586	2895	X	X				
Gemmi	GFU	Upper Valais	rock glacier, solifluction lobe	614800	139500	2750		X		X	X	
Grosses Gufer	GGU	Upper Valais	rock glacier	649350	141900	2600		X		X	X	
Gruben	GRU	Upper Valais	rock glacier	640410	113500	2880		X		X	X	
Hungerlitaelli	HUT	Upper Valais	rock glacier	621500	115500	3000		X		X		
Jungfraujoch	JFJ	Bernese Oberland	crest	641000	155120	3750	X					
Lapires	LAP	Lower Valais	rock glacier, talus slope	588070	106080	2700	X	X	X	X		X
Stabbio di Largario	LAR	Ticino	rock glacier	719000	148500	2550		X		X	X	
Matterhorn	MAT	Upper Valais	crest	618399	92334	3300	X					
Muot da Barba Peider	MBP	Engadine	talus slope	791300	152500	2980	X					
Alpage de Mille	MIL	Lower Valais	rock glacier	581800	96800	2500		X		X		
Monte Prosa	MPR	Ticino	rock glacier	687450	157700	2600		X		X	X	
Muragl	MUR	Engadine	rock glacier	791025	153750	2750	X	X		X	X	
Murtèl-Corvatsch	COR	Engadine	rock glacier, talus slope	783158	144720	3300	X	X	X	X	X	X
Réchy	REC	Lower Valais	rock glacier	605900	113300	3100		X		X	X	
Ritigraben	RIT	Upper Valais	rock glacier	631734	113745	2634	X					X
Schafberg	SBE	Engadine	rock glacier	790750	152775	2760	X	X				
Valle di Sceru	SCE	Ticino	rock glacier, talus slope	720130	145580	2560		X		X		
Schilthorn	SCH	Bernese Oberland	crest	630365	156410	3000	X	X	X			X
Stockhorn	STO	Upper Valais	crest	629878	92876	3379	X	X	X			X
Tsarmine	TMI	Lower Valais	rock glacier	605320	99400	2600		X		X		
Tsaté	TSA	Lower Valais	crest	608490	106400	3070	X	X				
Yettes Condjà	YET	Lower Valais	rock glacier	588280	105000	2800		X		X		