Swiss Permafrost Bulletin 2023

1 October 2022 to 30 September 2023

Annual report #5 on permafrost observation in the Swiss Alps

Swiss Permafrost Monitoring Network PERMOS

May 2024

Imprint

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Data collection

The maintenance of field installations and the data acquisition at the PERMOS sites are the responsibility of the seven PERMOS Partner Institutions: ETH Zurich (ETHZ), Universities of Fribourg (UniFR), Innsbruck (UIBK), 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).

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Suggested citation

PERMOS 2024. Swiss Permafrost Bulletin 2023. Noetzli, J. and Pellet, C. (eds.). No. 5, 25 pp., doi: 10.13093/permos-bull-24.

Data availability

All PERMOS data are available online at https://www.permos.ch/data-portal and are subject to the PERMOS Data Policy (CC-BY 4.0). This report is based on the version 2024 of the PERMOS data set: https://doi.org/10.13093/permos-2024-01.

Cover page

Rock temperature logger close to the summit station of the Corvatsch cable car at 3300 m asl. Photo: M. Lichtenegger.

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 in permafrost in the Swiss Alps based on field measurements of ground temperatures, electrical resistivities and rock glacier velocities.

The hydrological year 2023 lasted from October 2022 to September 2023 and was the warmest since measurements began in 1864 with a mean annual air temperature 2.7 °C above the 1961–1990 average. The hydrological year 2023 was characterized by a very mild and dry winter with well below-average snow heights in the East and below-average snow heights in the West, a cool spring, and very warm atmospheric conditions in summer and autumn.

As a result of these meteorological conditions, the mean annual ground surface temperature in the hydrological year 2023 decreased slightly at most sites and landforms compared to the previous year but remained on a high level. The persistently warm surface conditions led to relatively thick active layers (ALT) in 2023, which were at or near record level. The temperature signals from the surface penetrate to greater depths with a delay of a few months and more and filtered. At 10 m depth, permafrost temperature were a few tenths of degrees higher in 2023 than in 2022 at most sites. At the rock glacier sites, however, permafrost temperatures slightly decreased in 2023 compared to 2022. In the coarse blocky surfaces, the cooling during the two snow-poor winters was more effective and could not be fully compensated for by the hot summers of 2022 and 2023. In general, permafrost temperatures at a depth of 10 m after the hydrological year 2023 are only slightly below the record value measured for most locations in 2020 or 2021.

The permafrost electrical resistivities measured in 2023 showed contrasting evolutions compared to 2022, with a decrease of –13% at Stockhorn and an increase of +10% and +20% at Attelas and Murtèl-Corvatsch. This is in line with the permafrost temperature observations and indicates a continued increase in liquid water content within the permafrost at Stockhorn, which is considered a direct consequence of ground ice degradation. In contrast the resistivity increase in coarse blocky terrain is consistent with a lower liquid water content within the permafrost due to the lower temperatures recorded.

Rock glacier velocities exhibited regionally different behaviours with an acceleration in the western part of the Swiss Alps and a deceleration in the central and eastern parts. Maximum changes with respect to 2022 were observed at Lapires in the Lower Valais with an increase of +29% and at Largario in the Southern Alps with a decrease of –34%.

Overall, the hydrological year 2023 was characterized by warm conditions at both the surface and in the uppermost meters of the ground, which led to large or even record ALTs. At 10 meters depth, permafrost temperatures rose slightly at most locations because of the hot summer of 2022. A slight cooling was observed at the rock glacier sites as a result of the long period of below-average snow depths in winter of 2023. At greater depth (20 m) and in response to long-term climatic changes, permafrost temperatures remained at or close to record high levels. Depending on the location, the ground ice content increased or decreased slightly compared to the previous year and the rock glacier velocities changed only slightly.

The data over more than 20 years show a general trend of permafrost warming, ground ice degradation and rock glacier acceleration in the Swiss Alps. This general trend varies with the spatially inhomogeneous permafrost characteristics and can be overlaid by short-term variations in meteorological conditions.

Zusammenfassung

Das Schweizer Permafrost-Beobachtungsnetz PERMOS dokumentiert Zustand und Veränderungen des Permafrosts in den Schweizer Alpen anhand von Feldmessungen von Bodentemperaturen, elektrischem Widerstand und Blockgletscher-Geschwindigkeiten.

Das hydrologische Jahr 2023 dauerte von Oktober 2022 bis September 2023 und war das wärmste seit Beginn der Messungen im Jahr 1864 mit einer mittleren Jahreslufttemperatur von 2.7 °C über dem Durchschnitt von 1961–1990. Das hydrologische Jahr 2023 war geprägt durch einen sehr milden und trockenen Winter mit deutlich unterdurchschnittlichen Schneehöhen im Hochwinter, einen kühlen Frühling und sehr warme atmosphärische Bedingungen im Sommer und Herbst.

Infolge dieser meteorologischen Bedingungen ging die mittlere jährliche Bodenoberflächen-temperatur im hydrologischen Jahr 2023 an den meisten Standorten und Landformen im Vergleich zum Vorjahr leicht zurück, blieb aber weiterhin auf hohem Niveau. Die anhaltend warmen Oberflächenbedingungen führten zu relativ mächtigen Auftauschichten (ALT) im Jahr 2023 auf oder nahe bei Rekordniveau. Die Temperatursignale der Oberfläche erreichen die grösseren Tiefen erst einige Monate verzögert und gedämpft. In 10 m Tiefe waren die Permafrosttemperaturen an den meisten Standorten wenige Zehntel Grad Celsius höher als im Vorjahr. An den Blockgletscher Standorten dagegen waren die Permafrosttemperaturen leicht tiefer in 2023 als in 2022. In diesen grobblockigen Oberflächen hat die Abkühlung in den beiden schneearmen Wintern überwogen und konnte durch die heißen Sommer 2022 und 2023 nicht vollständig kompensiert werden. Generell liegen Permafrosttemperaturen in einer Tiefe von 10 m nach dem hydrologischen Jahr 2023 nur wenig unter dem Rekordwert, der für die meisten Standorte im Jahr 2020 oder 2021 gemessen wurde.

Der 2023 gemessene elektrische Widerstand im Permafrost entwickelte sich im Vergleich zu 2022 unterschiedlich, mit einem Rückgang von –13 % am Stockhorn und einer Zunahme um +10% und +20% in Les Attelas und Murtèl-Corvatsch. Dies stimmt mit den Beobachtungen der Permafrosttemperaturen überein und deutet auf einen anhaltenden Anstieg des Flüssigwassergehalts im Permafrost am Stockhorn, der als direkte Folge des Abbaus von Bodeneis angesehen wird. Im Gegensatz dazu deutet der Anstieg des spezifischen Widerstandes im grobblockigen auf einen niedrigeren Anteil an Flüssigwasser im Permafrost aufgrund der leicht tieferen Permafrosttemperaturen in den Blockgletschern.

Die Geschwindigkeiten der Blockgletscher waren regional unterschiedlich mit einer Beschleunigung in westlichen Teil und einer leichten Verlangsamung in den zentralen und östlichen Teilen der Schweizer Alpen. Die grössten Änderungen gegenüber dem Vorjahr wurden in Lapires im Unterwallis mit +29% und in Largario in den Südalpen mit –34% beobachtet.

Insgesamt war das hydrologischen Jahr 2023 durch warme Permafrostbedingungen an der Oberfläche und in den obersten Metern gekennzeichnet, was zu einer mächtigen Auftauschicht führte. In größerer Tiefe stiegen die Permafrosttemperaturen in 10 m Tiefe an den meisten Standorten als Folge des Hitzesommers 2022 leicht an. Eine leichte Abkühlung wurde an den Blockgletschern beobachtet als Folge der lange unterdurchschnittlichen Schneehöhen im Winter 2023. In größerer Tiefe und als Reaktion auf die langfristigen klimatischen Veränderungen blieben die Permafrosttemperaturen auf oder nahe den Rekordwerten. Der Bodeneisgehalt hat je nach Standort im Vergleich zum Vorjahr wenig zu- oder abgenommen und die Blockgletschergeschwindigeiten änderten nur wenig.

Die Messungen über mehr als 20 Jahre dokumentieren einen generellen Trend von Permafrost-Erwärmung in den Schweizer Alpen, zusammen mit einer Abnahme des Eisgehalts im Untergrund und einer Beschleunigung der Blockgletscher. Dieser allgemeine Trend variiert mit der räumlichen Variabilität der Permafrostbedingungen und kann durch kurzfristige Schwankungen der meteorologischen Bedingungen überlagert werden.

Résumé

Le réseau suisse de mesure du permafrost PERMOS documente l'état et les changements du permafrost dans les Alpes suisses à l'aide de mesures sur le terrain des températures du sol, de la résistance électrique et de la vitesse des glaciers.

L'année hydrologique 2023, qui a duré d'octobre 2022 à septembre 2023, a été la plus chaude depuis le début des mesures en 1864, avec une température annuelle moyenne de l'air de 2,7 °C supérieure à la moyenne de 1961-1990. L'année hydrologique 2023 a été caractérisée par un hiver très doux et sec avec des hauteurs de neige nettement inférieures à la moyenne, un printemps frais et des conditions atmo¬sphé¬riques très chaudes en été et en automne.

En raison de ces conditions météorologiques, la température moyenne annuelle à la surface du sol a légèrement diminué durant l'année hydrologique 2023 par rapport à l'année précédente tout en restant à un niveau élevé et ce sur la plupart des sites. Les conditions chaudes persistantes à la surface ont entraîné des épaisseurs de couche active (ALT) relativement grandes en 2023, qui dépassent ou approchent du niveau record. A 10 m de profondeur, les températures du pergélisol étaient supérieures de quelques dixièmes de degrés à celles de 2022 pour la plupart des sites à l'exception des sites de glaciers rocheux où les températures ont légèrement diminué en 2023. Sur ces sites, dont la surface est constituée de gros blocs, le refroidissement dû aux deux derniers hivers peu enneigés a été plus marqué et n'a pas pu être entièrement compensé par les étés chauds de 2022 et 2023. De façon général les températures du pergélisol à 10 m de profondeur en 2023 sont légèrement inférieures au niveau record mesuré pour la plupart mesuré en 2020 ou 2021.

Les résistivités électriques mesurées dans le pergélisol en 2023 ont connu des évolutions contrastées comparé à 2023 avec une diminution de -13% au Stockhorn et une augmentation de +10% et +20% aux Attelas et à Murtèl-Corvatsch. Ces observations sont en accord avec les températures mesurées et indiquent une augmentation du contenu en eau dans le pergélisol au Stockhorn, qui est considérée comme une conséquence directe de la fonte de la glace du pergélisol. L'augmentation des résistivités observée sur les sites dont la surface est constituée de gros blocs est, elle, cohérente avec une diminution du contenu en eau en raison des températures plus basses.

Les vitesses des glaciers rocheux ont présenté des comportements régionaux différents, avec une accélération dans l'ouest des Alpes suisses et une décélération dans les parties centrales et orientales. Les changements les plus importants par rapport à 2022 ont été enregistré à Lapires dans le Bas-Valais avec une augmentation de +29% et à Largario dans le sud des Alpes avec une diminution de -34%.

Dans l'ensemble, l'année hydrologique 2023 a été caractérisée par des conditions chaudes à la surface et dans les premiers mètres du sol, conduisant à des ALT importantes ou même record. À 10 mètres de profondeur, les températures du pergélisol ont légèrement augmenté sur la plupart des sites à la suite de l'été chaud de 2022. Un léger refroidissement a toutefois été observé sur les sites de glaciers rocheux en réponse aux quantités de neiges largement inférieures à la moyenne au cours de l'hiver 2023. À plus grande profondeur (20 m) et en réponse aux changements climatiques à long terme, les températures du pergélisol sont restées à des niveaux record ou proches de ceux-ci. Selon le site, la quantité de glace du pergélisol a augmenté ou diminué par rapport à l'année précédente et la vitesse des glaciers rocheux n'a que faiblement changé.

Les données recueillies sur plus de 20 ans montrent une tendance générale au réchauffement du pergélisol, à la diminution de la quantité de glace dans le sol et à l'accélération des glaciers rocheux dans les Alpes suisses. Cette tendance générale est influencée par la variabilité spatiale des du pergélisol et peut être masquée par des fluctuations à court terme dues aux conditions météorologiques.

Riassunto

La Rete svizzera di osservazione del permafrost PERMOS documenta lo stato e i cambiamenti del permafrost nelle Alpi svizzere attraverso misure sul terreno della temperatura del suolo, della resistività elettrica e della velocità dei ghiacciai rocciosi.

L'anno idrologico 2023, durato dal 1° ottobre 2022 al 30 settembre 2023, è stato il più caldo dall'inizio delle misurazioni nel 1864, con una temperatura media annua dell'aria di 2.7°C superiore alla media 1961–1990. L'anno idrologico 2023 è stato caratterizzato da un inverno molto mite e secco, con delle altezze di neve ben al di sotto della media, una primavera fresca e delle condizioni atmosferiche molto calde in estate e in autunno.

Come risultato di queste condizioni meteorologiche, la temperatura media annua della superficie del suolo durante l'anno idrologico 2023 è diminuita leggermente rispetto all'anno precedente in tutti i siti e per tutte le forme del rilievo, pur rimanendo a un livello elevato. Le condizioni di caldo persistente alla superficie del suolo hanno portato a spessori dello strato attivo (ALT) relativamente elevati nel 2023, che hanno raggiunto o sfiorato i livelli record. I segnali di temperatura dalla superficie penetrano a profondità maggiori in maniera attenuata e con un ritardo di alcuni mesi. A 10 m di profondità, le temperature del permafrost sono state di qualche decimo di grado centigrado più alte rispetto al 2022 nella maggior parte dei siti. Nei siti con i ghiacciai rocciosi, tuttavia, le temperature del permafrost sono leggermente diminuite nel 2023 rispetto all'anno precedente. Nelle superfici a blocchi grossolani, il raffreddamento durante i due inverni poveri di neve è stato più efficace ed è stato compensato solo in parte dalle estati caldi del 2022 e 2023. In generale, le temperature del permafrost a 10 m di profondità dopo l'anno idrologico 2023 sono solo leggermente inferiori al valore record misurato per la maggior parte dei siti nel 2020 o nel 2021.

Le resistività elettriche del permafrost misurate nel 2023 hanno mostrato evoluzioni contrastanti rispetto al 2022, con una diminuzione del -13% al Stockhorn e un aumento del +10% e del +20% agli Attelas e Murtèl-Corvatsch. Questi risultati sono in linea con le osservazioni della temperatura del permafrost e indicano un continuo aumento del contenuto di acqua liquida all'interno del permafrost allo Stockhorn, il quale è considerato una conseguenza diretta della degradazione del ghiaccio del suolo. Al contrario, l'aumento della resistività nei terreni grossolani a blocchi è coerente con un minore contenuto di acqua liquida all'interno del permafrost a causa delle temperature più basse registrate. Le velocità dei ghiacciai rocciosi hanno mostrato comportamenti diversi a livello regionale, con un'accelerazione nella parte occidentale delle Alpi svizzere e una decelerazione nelle parti centro-meridionali e orientali. Le variazioni massime rispetto al 2022 sono state osservate nei siti dei Lapires nel basso Vallese, con un aumento del +29%, e di Stabbio di Largario nel sud delle Alpi, con una diminuzione del -34%.

Nel complesso, l'anno idrologico 2023 è stato caratterizzato da condizioni calde sia in superficie sia nei primi metri di profondità del terreno, che hanno portato a ALT elevate o addirittura da record. A causa dell'estate calda del 2022, a 10 m di profondità le temperature del permafrost sono aumentate leggermente nella maggior parte dei siti. Nei siti con i ghiacciai rocciosi è stato osservato un leggero raffreddamento a causa del lungo periodo di innevamento al di sotto della media registrato nell'inverno del 2023. A profondità maggiori e in risposta ai cambiamenti climatici a lungo termine, le temperature del permafrost sono rimaste a livelli record o quasi. A seconda del sito, il contenuto di ghiaccio nel suolo è aumentato o diminuito leggermente rispetto all'anno precedente e le velocità dei ghiacciai rocciosi sono cambiate di poco. I dati raccolti in oltre 20 anni mostrano una tendenza generale al riscaldamento del permafrost, alla diminuzione del volume di ghiaccio nel suolo e all'accelerazione dei ghiacciai rocciosi nelle Alpi svizzere. Questa tendenza generale è influenzata dalla variabilità spaziale delle proprietà del permafrost e può essere mascherata da fluttuazioni a breve termine dovute alle condizioni meteorologiche.

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1 Introduction

The Swiss Permafrost Monitoring Network (PERMOS, www.permos.ch) documents the state and changes in permafrost in the Swiss Alps based on field measurements. Results are published annually in the *Swiss Permafrost Bulletin* since 2019. This report covers the hydrological year 2023, i.e. the period from 1 October 2022 to 30 September 2023. The reporting is based on the hydrological year because of the significant influence of the snow cover and its timing on the permafrost conditions.

Permafrost is an invisible thermal subsurface phenomenon found in cold regions worldwide. It is defined as ground material remaining at or below 0 °C for at least two consecutive years. In the Swiss Alps, permafrost is typically found above the treeline at elevations above ca. 2500 m asl. It underlies about 5% of the Swiss territory and exists in bedrock and rock debris slopes of the high mountain areas. Permafrost reacts sensitively to changing atmospheric conditions and is therefore defined as one of the Essential Climate Variables (ECVs) by the Global Climate Observing System (GCOS) of the World Meteorological Organization (WMO). The three ECV products, which are the defined ECV key indicator variables, are: i) permafrost temperature, ii) active layer thickness (ALT) and iii) rock glacier velocity (see WMO 2022). Internationally, permafrost is observed in the framework of the Global Terrestrial Network for Permafrost (GTN-P, Streletskiy et al. 2021), to which PERMOS contributes.

The PERMOS monitoring strategy is based on field measurements of three complementing variables, which are in line with the products and requirements of the ECV «Permafrost» (WMO 2022):

1) Ground temperature near the surface and at depth,
2) Permafrost electrical resistivity, and
3) Rock glacier velocity.

The active layer thickness (ALT), i.e. the maximum seasonal penetration depth of the 0 °C isotherm, is derived from continuous temperature time series measured at multiple depths in boreholes. Meteorological data are obtained at some of the sites. Mass movements (i.e., rock falls and rock avalanches) originating from permafrost areas are documented in a catalogue.

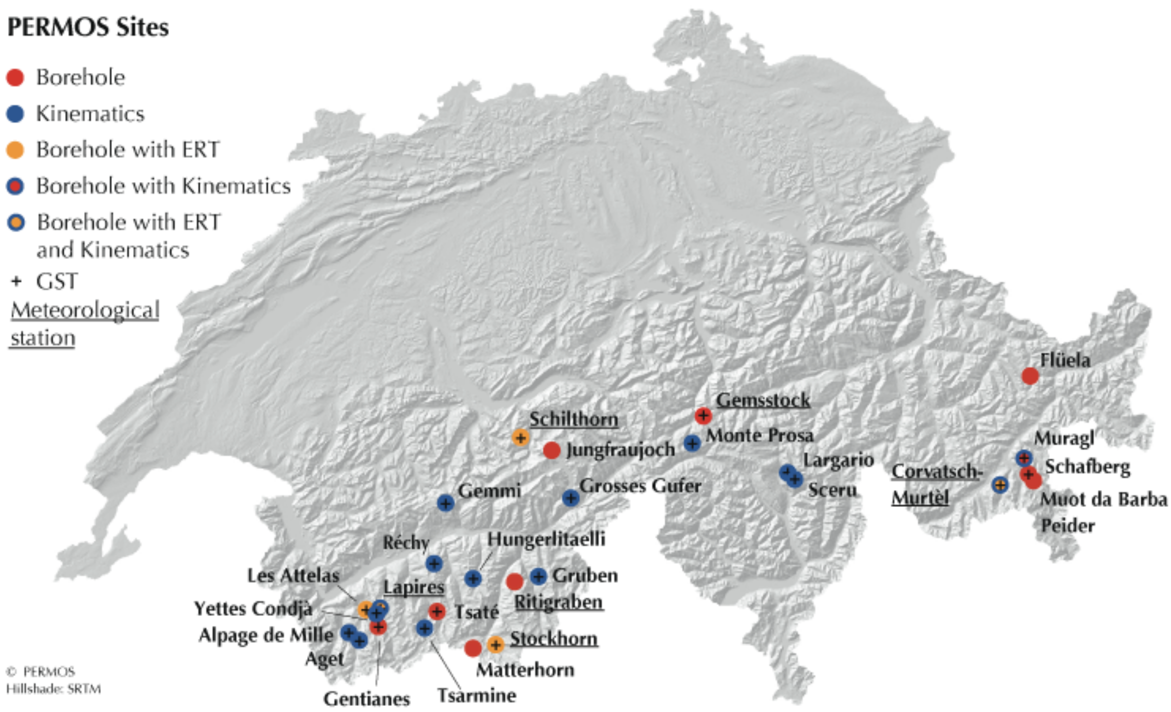

Figure 1.1. PERMOS field sites and measured variables in 2023.

Within PERMOS, 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). Most of the available permafrost monitoring sites were installed in the framework of research projects and have been operationally maintained for decade(s) by the partner institutions.

In 2023, the PERMOS network included 27 field sites (Figure 1.1, Table A.1): Ground temperatures are measured at 15 sites in 26 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. 2022) and geophysical surveys are conducted annually along permanently installed profiles at 5 sites. Rock glacier velocities are measured by annual terrestrial surveys at 15 sites (with 1 to 2 rock glaciers per site) and 8 of these are additionally equipped with a permanently installed GNSS device. Ground surface temperature (GST) is measured at 22 of the sites, with a total of 225 locations in 2023.

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 instrument maintenance and data collection. The PERMOS Office (WSL-SLF and UniFR) 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 in 2022/2023

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 temperature changes at the ground surface in periods with little or no snow, and all year round for locations where no thick snow cover can develop, such as near-vertical slopes or wind-blown ridges. The onset of an insulating snow cover in early winter and the time when the ground surface becomes snow free in spring are therefore relevant: 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 below is based on MeteoSwiss (2023, 2024) and Pielmeier et al. (2024).

The hydrological year 2023 started with the third warmest autumn on record. The early start of winter at high elevations (>2000 m asl.) in early November was followed by a very mild and very dry winter. The amount of precipitation recorded throughout the winter was 40–65% of the 1991–2010 norm in the eastern, central, and southern Alps, whereas it was 70–90% in the western part. Between mid-February and mid-March, hardly any snow fall was recorded, leading to the lowest snow depths in the Swiss Alps since 1962 or earlier (Figures 2.1 and 2.2). End of March and April were characterized by significantly above-average amounts of precipitation in the Alps yielding above-average snow depth in the Lower Valais and Bernese Oberland and slightly below-average values in the other regions. The temperature in May 2023 was around average with above-average precipitation, while June 2023 was extremely sunny and warm leading to an earlier disappearance of the snow cover than for the long-term average in all regions.

Figure 2.1. View of the Schafberg and Muot da Barba Peider above Pontresina in the Upper Engadine in February 2023, when snow heights were clearly below average. Photo: M. Phillips.

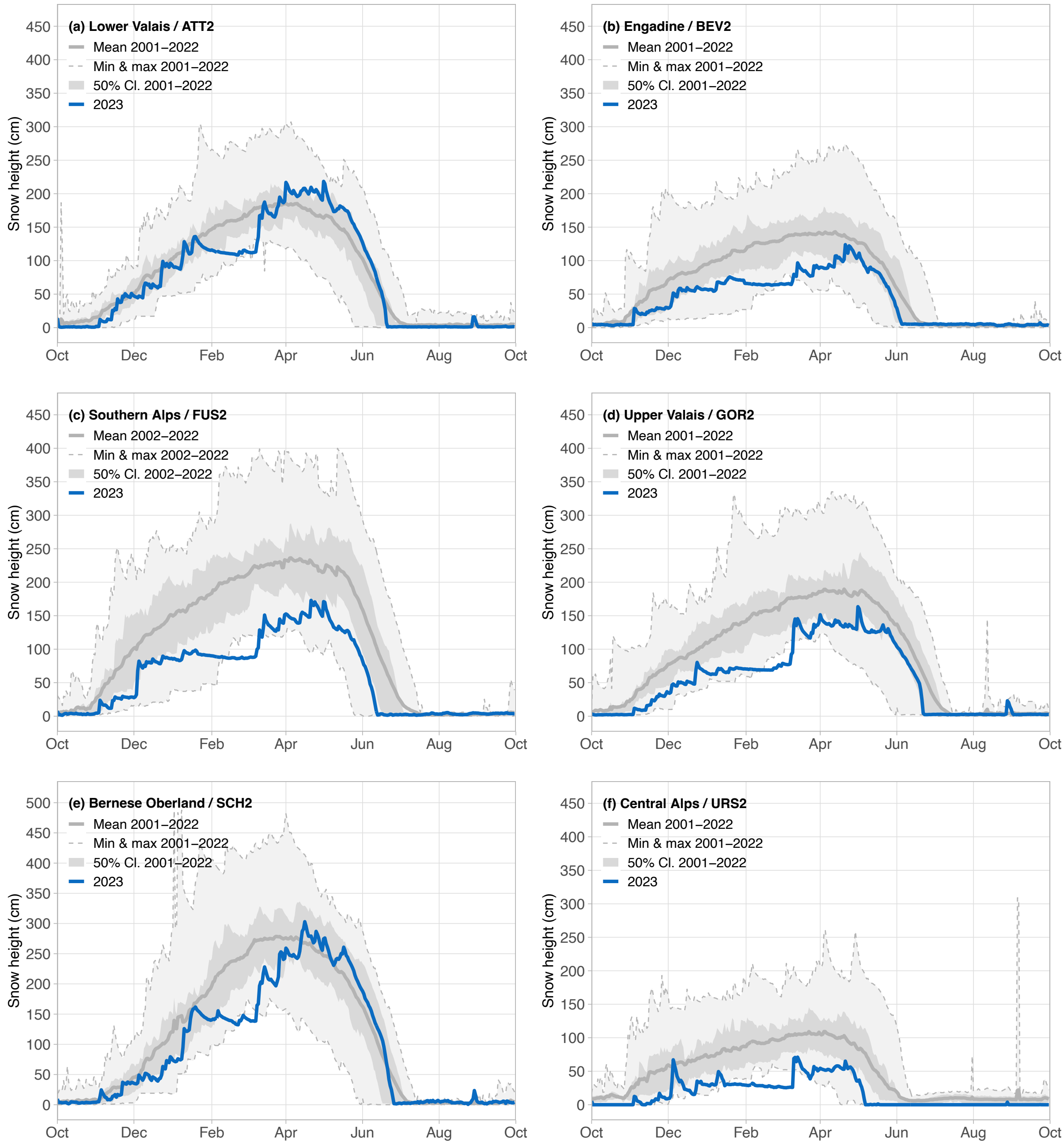

Figure 2.2. Snow height at six IMIS stations during winter 2023 compared to the mean, 25th and 75th percentiles of the period 2001–2022. Data were corrected for outliers and aggregated to daily median values. The stations represent different regions in the Swiss Alps (below the region, the name of the 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.

Switzerland experienced the fifth warmest summer on record, with two pronounced heatwaves on the northern side of the Alps and three on the southern side. The August 2023 heat wave was the longest and warmest heat wave ever recorded at this time of the year. During the night from the 20th to the 21st of August 2023, a new record elevation of the 0 °C isotherm was registered at 5298 m asl. The amount of precipitation during summer was mostly at or slightly above average in Valais, south and eastern Switzerland, whereas it remained below-average in the other regions.

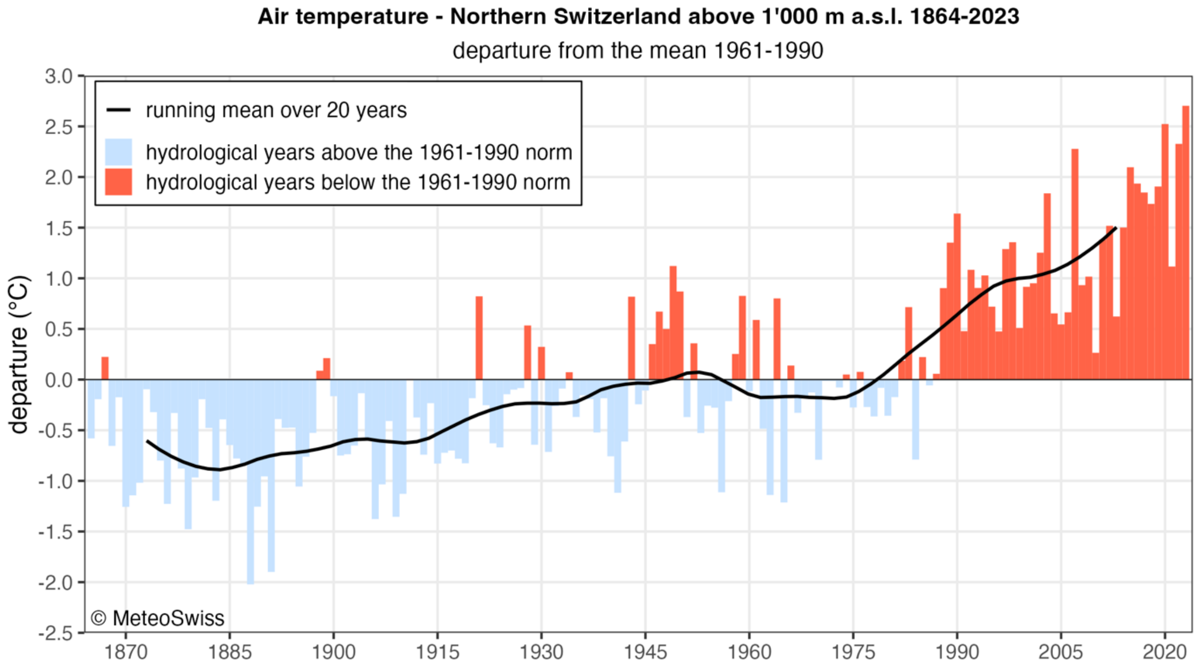

Figure 2.3. Air temperature deviation from the 1961–1990 norm based on homogenized data series for Swiss stations above 1000 m asl. for 1864–2023. Annual values refer to the hydrological year (October to September). Adapted from MeteoSwiss (2023).

In summary, the hydrological year 2023 was characterized by a very mild and dry winter with clearly below-average snow heights for a long period, a colder and wet spring, and by very warm atmospheric conditions in summer and autumn. Overall, it was the warmest hydrological year since the start of the measurements in 1864 (the calendar year 2023 was the second warmest year). The mean annual air temperature (MAAT) was 2.7 °C above the 30-year average 1961–1990 (the reference period recommended for monitoring long-term climate change by WMO) and 1.5 °C above the most recent normal period 1991–2020 (Figure 2.3).

3 Thermal state of permafrost

Ground temperatures are direct, quantitative, and comparable observations of the permafrost thermal state and constitute the basis of climate-related monitoring of permafrost in the international framework of GCOS (WMO 2022) and GTN-P (Streletskiy et al. 2021). Continuous ground temperature measurements in permafrost can also be used to derive the active layer thickness (ALT, i.e., the maximum thickness of the layer that thaws annually during summer, Section 3.2). The point information obtained in the permafrost from observations in boreholes (Section 3.3) is complemented by spatially distributed measurements of the ground surface temperature (Section 3.1).

3.1 Ground surface temperatures

Ground surface temperature (GST) observations capture the thermal conditions at the ground surface, which subsequently penetrate into the ground and to larger depths with increasing delay and attenuation. Spatially distributed measurements allow to assess the spatial variability related varying topographic settings or ground surface characteristics. GST result from the energy balance at the ground surface, which is predominantly influenced by solar radiation and air temperature during snow-free periods (e.g., Hoelzle et al. 2022). During the snow season, the ground surface is insulated from atmospheric conditions. Therefore, GST are critically influenced by the timing of the snow cover.

The GST data loggers are distributed close to boreholes, along geophysical profiles and next to geodetic survey points (Figure 3.1). Loggers are buried a few decimetres to shield them from direct solar radiation, which would cause warming of the casing. Recording intervals are 1–3 hours, depending on the type of device used. Individual GST time series are aggregated to daily mean values and gap-filled applying the quantile mapping approach described by Staub et al. (2017) on the entire PERMOS data set. Only the most complete GST time series are subsequently selected for analysis in this report: time series that (1) cover at least 5 years, (2) have values for 85% of the time after gap filling, and (3) include the reporting year. Daily GST site means are calculated for the time periods where data are available for all selected GST time series of the site. Annual mean values are calculated for each site based on monthly mean values. Criteria for data completeness to aggregate the time series to monthly and annual mean values follow those defined by the WMO for air temperatures (WMO 2017).

Figure 3.1. Miniature data logger recording ground surface temperatures in flat bedrock close to the Corvatsch summit station in the Upper Engadine at about 3300 m asl. Photo. M. Lichtenegger.

The mean annual ground surface temperature (MAGST) in the hydrological year 2023 was above the decadal mean 2012–2021 for all the sites with available data (17 out of 25 sites, Figures 3.2c and 3.3c). The effect of the late August 2023 heat wave (see Chapter 2) caused daily GST to reach new record values for this period of the year (Figures 3.2a and 3.3a). The record MAGST over hydrological years, which were observed in the years 2003, 2015 and 2022, were approached but not overpassed for most sites in 2023.

The long-term evolution of GST can be assessed using a running annual mean (rMAGST, Figure 3.2b, Figure 3.3b, Figure 3.4). Following the record warm summer 2022, rMAGST significantly increased at all sites and reached a new maximum at 13 out of 25 sites between January and April 2023 (e.g. at Aget and Réchy; cf. orange asterix in Figure 3.4). rMAGST then decreased until July2023 but increased again after the hot periods in late summer 2023. For the sites with longest GST time series (starting in the year 2000 or before) a warming rate of 0.4–0.6 °C is calculated based on linear regression on MAGST over a 25-year period.

The Ground Freezing Index (GFI) is defined as the sum of the negative daily temperatures during a hydrological year. GFI in 2023 is both slightly higher and lower than in the previous year, depending on the site (Figures 3.2d and 3.3d, blue bars). The Ground Thawing Index (GTI) is defined as the annual sum of positive daily temperatures and can only be determined for sites with data reaching until the end of September 2023. For these sites, GTI values are lower in 2023 than in the previous summer, reflecting the longer lasting snow cover and the cooler summer 2023 compared to the previous very warm year (Figures 3.1d and 3.2d, orange bars).

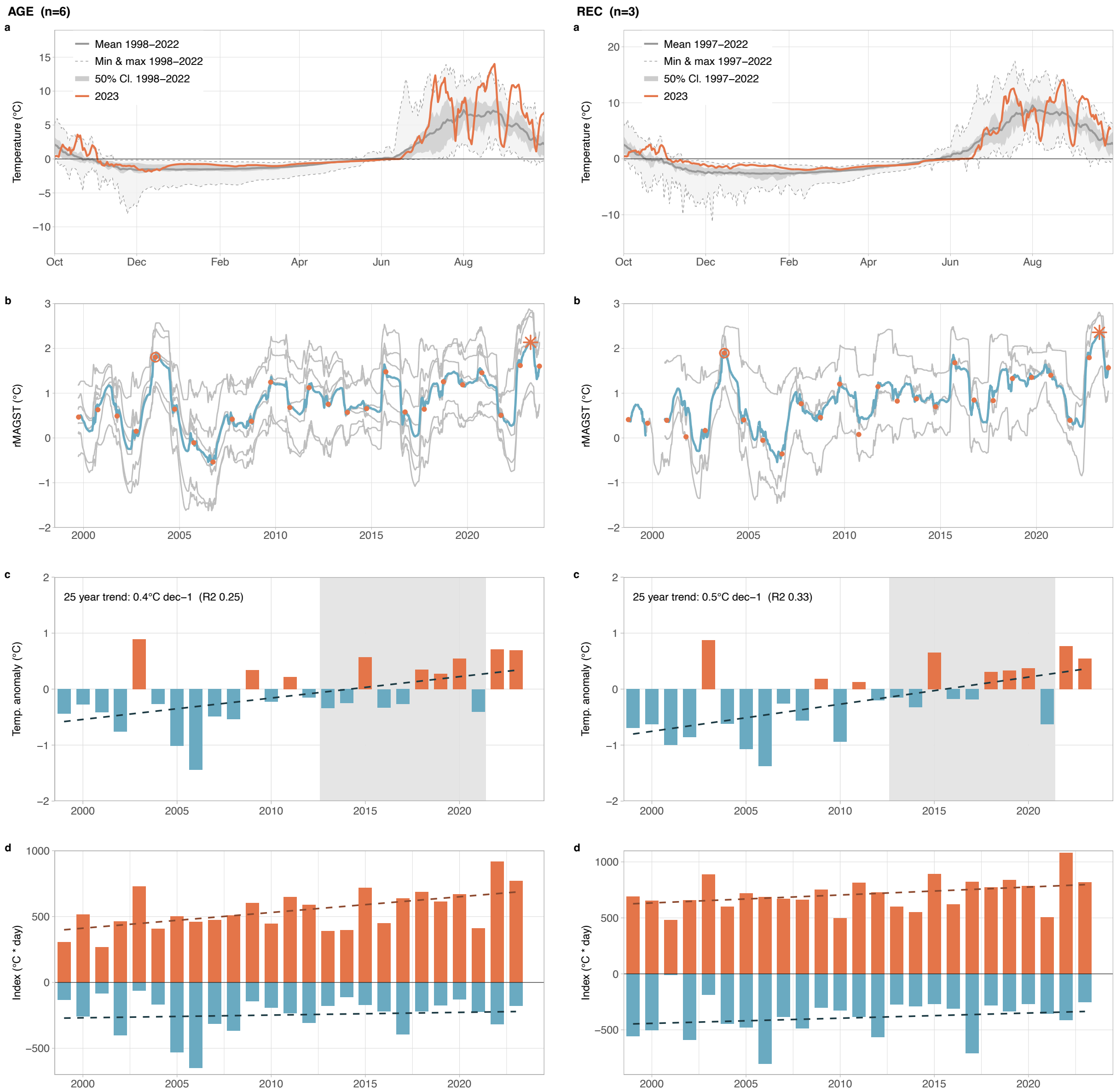

Figure 3.2. Ground surface temperatures at two rock glacier sites in the Lower Valais with long and complete time series: Aget (AGE, left) and Réchy/Bec de Bosson (REC, right). A) Daily mean GST at the sites during the hydrological year 2023 compared to all previous years. B) Running annual mean for the site mean (rMAGST, thick blue line) and all individual loggers in grey. Mean annual ground surface temperature (MAGST) is shown with orange dots. The maximum MAGST is marked with a circle, the maximum rMAGST with an asterisk. C) Departure of the MAGST from the 2012–2021 decadal mean. Trends for the last one and two decades are shown with dashed lines. D) Ground thawing and freezing indexes.

Figure 3.3. The same as figure 3.1, but for bedrock in the Corvatsch area in the Upper Engadine: flat bedrock with winter snow cover (COR_R, left) and near-vertical bedrock without winter snow cover (COR_W, right).

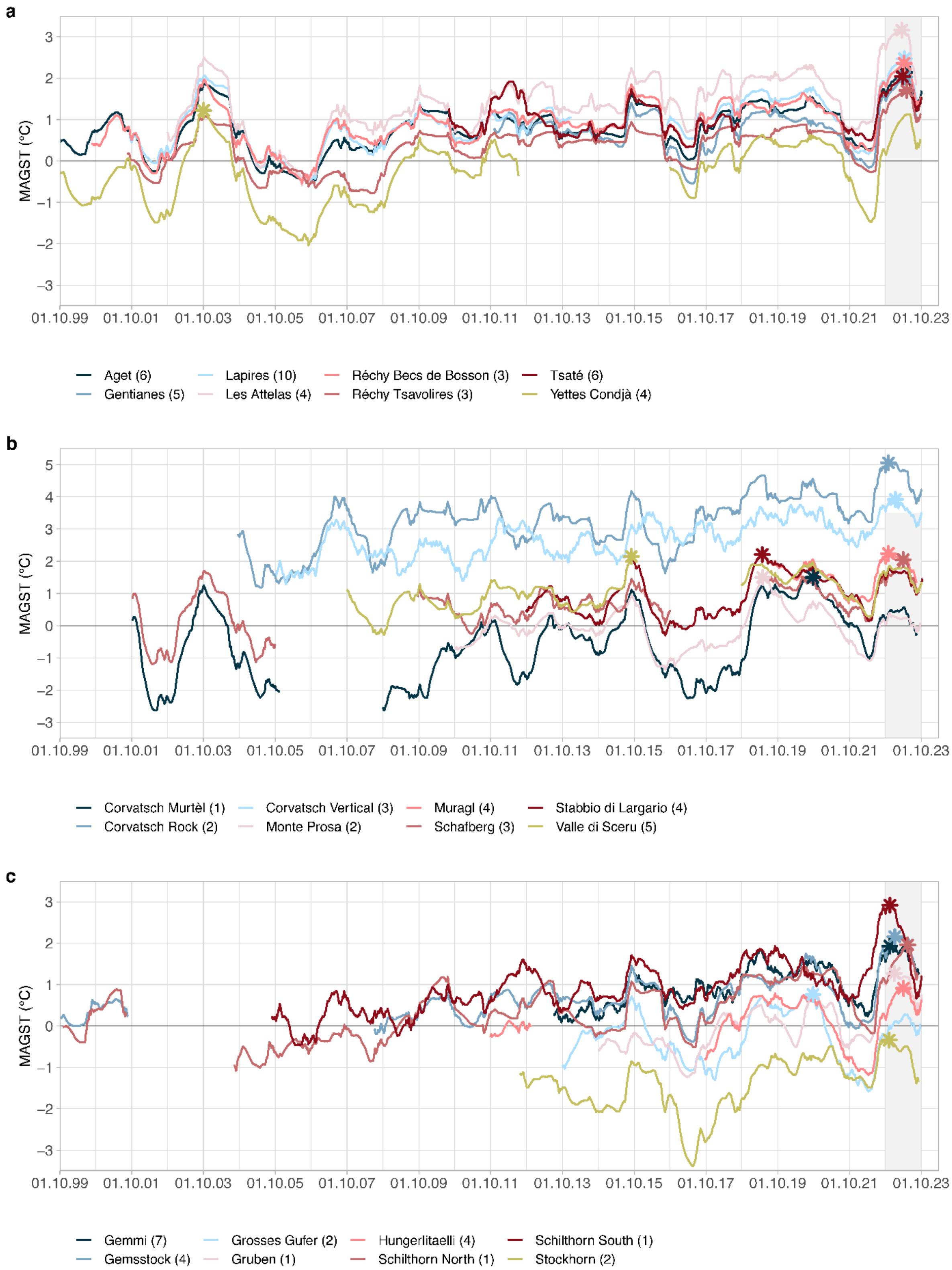

Figure 3.4: Running mean annual ground surface temperature (rMAGST) for sites in the Lower Valais (a), the eastern and Southern Swiss Alps (b), as well as the Upper Valais, central and Northern Swiss Alps (c). The maximum observed value of the rMAGST is indicated with an asterisk and the reporting period is shown with a grey background. Corvatsch Rock, Corvatsch Vertical and Gemsstock are measured in flat and near-vertical bedrock. All other sites are in uncon–solidated material (rock glaciers and talus slopes). Series depict site averages of several individual time series (the number of loggers used is given in brackets, cf. Figures 3.1b and 3.2b).

3.2 Active layer thickness

The maximum penetration depth of the 0 °C isotherm during summer/autumn defines the ALT. Its variations are influenced by thermal conditions at the ground surface and in the uppermost metres during one hydrological year. In addition, the magnitude of the changes is influenced by the ground ice content: due to latent heat exchange, inter-annual changes in ice-rich ground are considerably smaller than, for example, in bedrock where ground ice is only contained in pores and fractures.

The maximum thickness of the active layer during a year is calculated by linear interpolation of daily ground temperatures measured at multiple depths 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, particularly in ice-rich ground, quantitative changes in ALT must be interpreted with care. The direction of the trends as well as the general magnitude of the variations are considered robust.

The ALT in 2023 could be determined for 11 boreholes at 7 sites (ATT_0108, ATT0208, GEN_0222, LAP_0198, LAP_1108, LAP_1208, MBP_0319, RIT_0102, SCH_5318, STO_6000, STO_6100). For 4 of these boreholes, however, the resulting ALT is only a first estimate because the time series do not yet fully cover autumn/early winter and the ALT has potentially become even larger. For 6 boreholes at 4 sites, data for autumn 2023 have not yet been collected (FLU_0102, MBP_0196, MBP_0296, SBE_0190, SBE_0290, MAT_0205). For seven boreholes, the calculation of ALT is not possible due to either no permafrost (MUR_0199, GEM_0106), broken or unreliable sensors at the relevant depths (COR_0287, COR_0200, COR_0315, GEN_0102), or no sensor in the active layer (JFR_0195). In two boreholes on Schilthorn, the active layer can no longer be determined as it either reaches below the lowermost sensor (SCH5198), or the active layer no longer refreezes during winter (SCH_5200) and has formed a so-called talik.

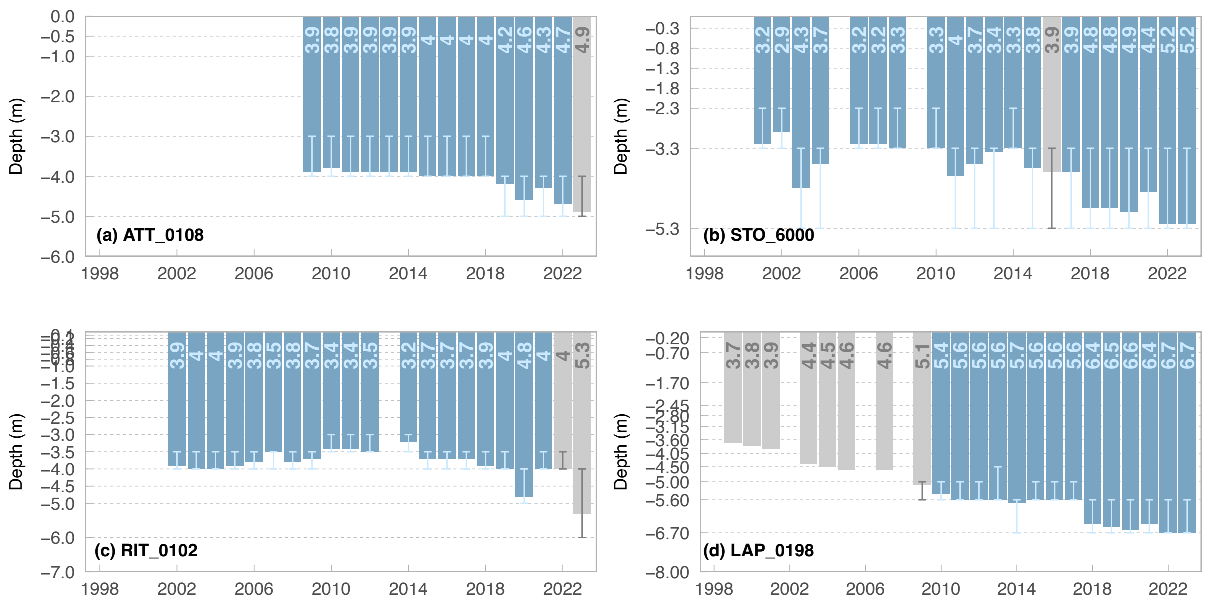

Figure 3.5: Active layer thickness (ALT) derived from borehole temperature data measured in the Attelas talus slope (a), on the Stockhorn Plateau (b), in the Ritigraben rock glacier (c), and in the Lapires talus slope (d). The uncertainty bars are defined by the thermistors used for the interpolation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

ALT calculated for the hydrological year 2023 were between 3.0 m (Muot da Barba Peider, MBP_0319) and >13 m (Schilthorn, SCH_5318). All ALT values that could be calculated were close to record values observed since the start of the measurements. A new maximum was observed for 5 time series (i.e. for 45% of the sites with available ALT data, Figure 3.5). The ALT of over 13 m observed on Schilthorn was measured in two boreholes SCH_5198 and SCH_5318, which are located only a few metres apart.

3.3 Permafrost temperatures

Ground temperatures in the uppermost metres below the surface react to short-term variations in meteorological conditions. These variations are increasingly filtered and delayed with depth. The signal delay is about half a year at 10 m depth. Seasonal variations can be measured down to the so-called depth of the zero annual amplitude (DZAA), which is typically at 15–20 m in permafrost ground in the Swiss Alps. Below the DZAA, ground temperatures react to multi-annual trends from atmospheric conditions with considerable delay (years to decades). 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 (see Chapter 4). When temperatures approach 0 °C in permafrost with a high ground ice content, temperature changes become minimal because of latent heat exchange during phase change. 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).

Continuous permafrost temperatures are recorded at multiple depths in 26 boreholes at 15 sites (see Appendix, Table A.1). The boreholes are instrumented with multi-sensor cables and automatic logging systems. Many of them are equipped with data transmission systems, while for the others the data is collected on site once a year at the end of the summer. 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.

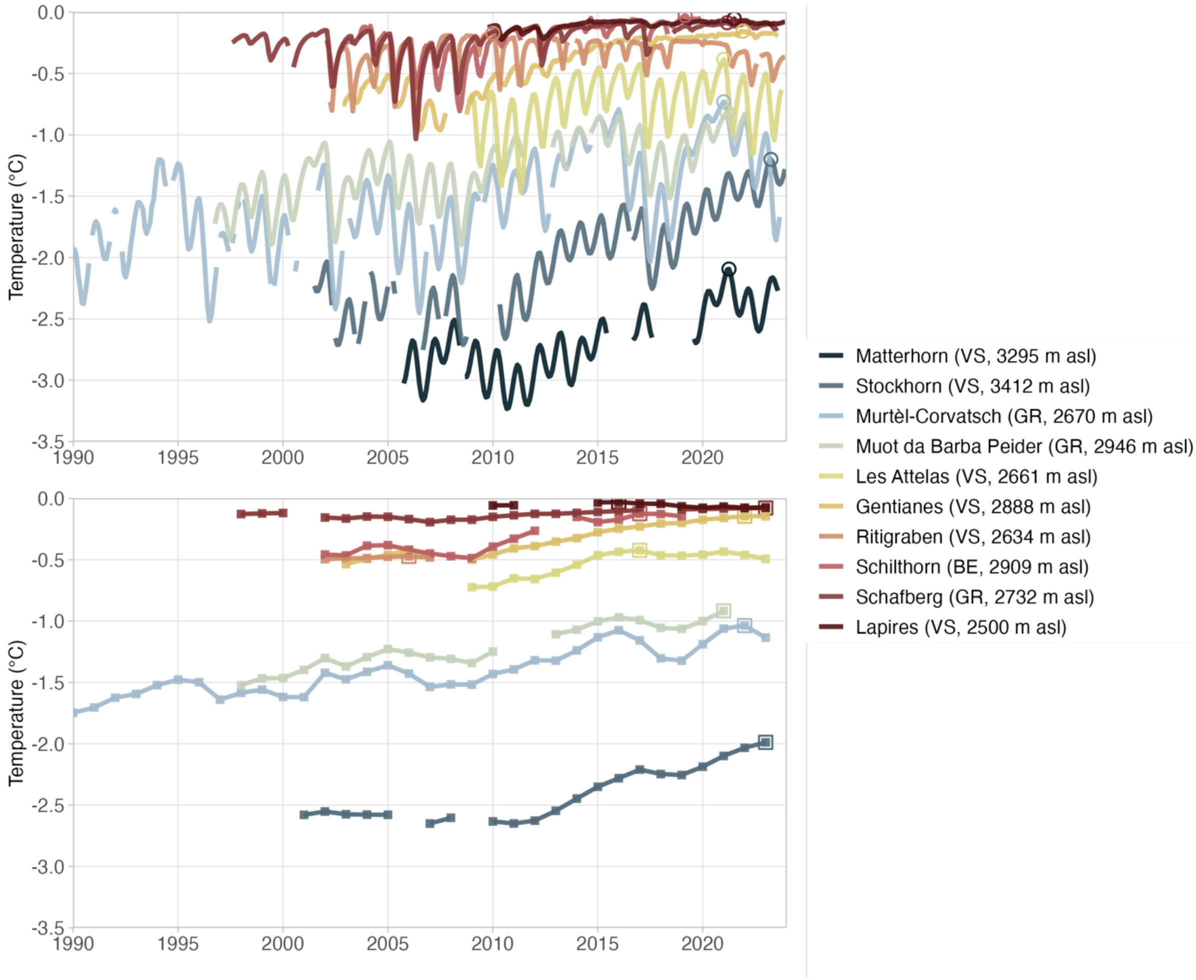

Figure 3.6. Permafrost temperatures measured in selected boreholes at 10 m (top, monthly means) and 20 m depth (bottom, means over the hydrological year). Maximum values for each time series are shown with circles (10 m depth, above) and squares (20 m depth, below).

During the hydrological year 2023, the mean annual permafrost temperatures at 10 m depth increased by a few tenths of degree Celsius compared to 2022 at the majority of the PERMOS borehole sites (Figure 3.6, upper panel). This increase is interpreted as the result of the warmer conditions in 2022 and 2023 as well as of the delayed response of the ground temperatures to the thermal conditions at the surface by about half a year. A new record high temperature was measured in winter 2023 at the Stockhorn site above Zermatt at 3400 m asl. This peak is due to the delayed impact of the summer 2022 heat wave. For most of the rock glaciers, such as Murtèl-Corvatsch or Ritigraben, a small 13decrease by a few tenths of degree was observed in 2023 in the permafrost temperatures at 10 m depth. This decrease is likely caused by the coarse blocks of the rock glacier surface that were sticking out of the snow cover during the snow poor winter 2023. The temperature decrease was more pronounced for sites in the eastern part of the Alps, where snow heights were lower.

A similar picture is observed for permafrost temperatures measured at depths of around 20 m, where they react with longer delay to atmospheric conditions and to longer-term trends. Here, permafrost temperatures are at or close to the maximum recorded in the past 10–20 years at all sites (Figure 3.6, lower panel). The strongest increase leading to a new record value was observed at Stockhorn. Several sites such as rock glacier Murtèl-Corvatsch and the Attelas talus slope exhibited a slight temperature decrease.

4 Electrical resistivities

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

Electrical resistivities are measured at five PERMOS sites along profiles varying between 55 and 220 m length. The typical ERT monitoring installation includes 43–50 permanently installed electrodes (stainless steel rods) that are connected to a water-proof box via cables (see Figure 4.1). The measurement device can then be connected to that box. 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 in September 2023 at Stockhorn. Photo: C. Hilbich.

The electrical resistivities measured at the PERMOS sites span over several orders of magnitudes (lowest at Schilthorn ~3’000 Ωm, and highest at Murtèl-Corvatsch ~300’000 Ωm, Figure 4.3). 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., in the centre of the profile and not too deep). With this delineation, the zones are considered representative for the monitored site. The active layer is excluded where possible to focus on the permafrost and zones subject to longer-term temporal variations.

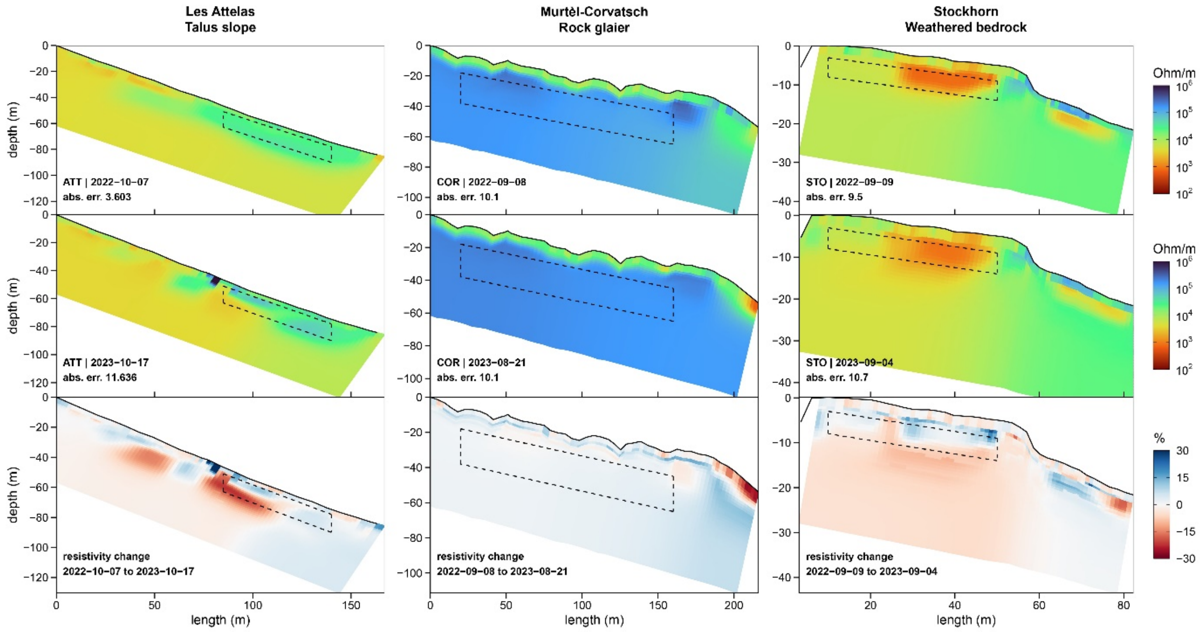

Figure 4.2. Electrical Resistivity Tomograms showing the resistivity distribution in 2022 (upper panel), 2023 (middle panel) and the resistivity difference (lower panel) between these two years for a talus slope (Les Attelas, left column), a rock glacier (Murtèl-Corvatsch, centre column) and a weathered bedrock site (Stockhorn, right column). The representative zones used to derive the time series shown in Figure 4.3 are indicated with dashed boxes.

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, which is considered a direct consequence of ground ice degradation and enhanced infiltration of water.

In 2023, ERT surveys were performed at all sites except for Schilthorn (due to large lightning protection installed during construction work in the vicinity, which interfered with the measurements). The measurement quality, however, was not satisfactory for the Lapires site (see Mollaret et al. 2019 for detailed description of the quality assessment and threshold). Compared to 2022, permafrost resistivities decreased by –13 % at Stockhorn, whereas they increased by 20% at Murtèl-Corvatsch and by 11% at Les Attelas. These results are consistent with the thermal conditions observed during the hydrological year 2023 (see Chapter 3) as well as with the sub-surface properties and topographical settings of the sites. Stockhorn is a bedrock site with comparatively low ice content, where ground temperatures are mostly controlled by conductive heat transport, thus explaining the observed decrease. This is in line with the larger ALT and the record high permafrost temperatures in 2023. Les Attelas and Murtèl-Corvatsch are coarse blocky sites with considerably higher ice content, where conductive heat transport occurs in parallel to latent heat exchange and heat convection/advection via ventilation in the coarse blocky surface layer, thus explaining the observed resistivity increase. At these sites, a slight permafrost temperature decrease at 10 and 20 m depth was observed in 2023.

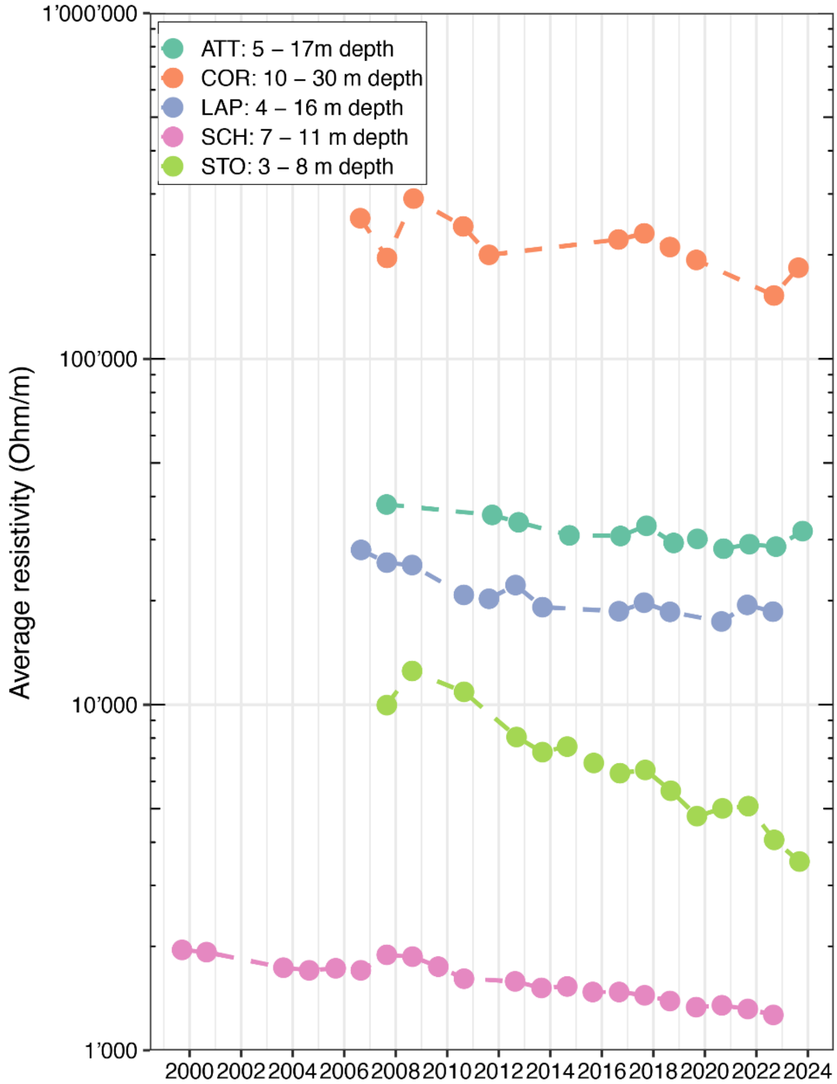

Figure 4.3. Average electrical resistivities of the permafrost zone (see Figure 4.2) at the end of summer for the 5 ERT sites in the PERMOS Network.

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 mostly reflect the changes in the deformation rate occurring at the shear horizon, located at about 20 m depth within the permafrost body, where most of the deformation occurs (Cicoira et al. 2020). Those changes are related to the evolution of the ground temperature and liquid water content between the upper surface of the permafrost (i.e., the permafrost table) and the shear horizon. Rock glacier velocities were shown to follow an exponential relation with multi-annual ground surface temperature forcing (i.e., increasing ground surface temperatures lead to an increase in velocity, see Staub et al. 2016).

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) and their spatially distributed annual and inter-annual changes (TGS).

Figure 5.1. GPS measurements at the front of the Grosses Gufer rock glacier in September 2023. Photo: M. Harkema.

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 to subsequently calculate the surface velocity. Control points (i.e., points located on stable areas) are used to 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 rock glacier based on their spatial distribution (i.e., located within the area of the rock glacier where surface displacements are dominantly related to permafrost creep) as well as data quality and completeness. These points are used to compute site averages (Figures 5.2 and 5.3).

During the hydrological year 2023, rock glacier velocities generally increased in the western part of the Swiss Alps and decreased in the central and eastern parts. Compared to 2022, an average increase of +16% and +9% were observed in the Lower and Upper Valais, and an average decrease of –21% and –7% were recorded in the Central/Southern Alps and the Engadine. The maximum decrease was observed at Largario (LAR, –34%, see Figure 5.2c) in the Southern Alps. The maximum increase was observed at Lapires (LAP, +29%, Figure 5.2a) in the Lower Valais region. Considering the Swiss average, rock glacier velocities did not significantly change between 2022 and 2023 (+ 1%).

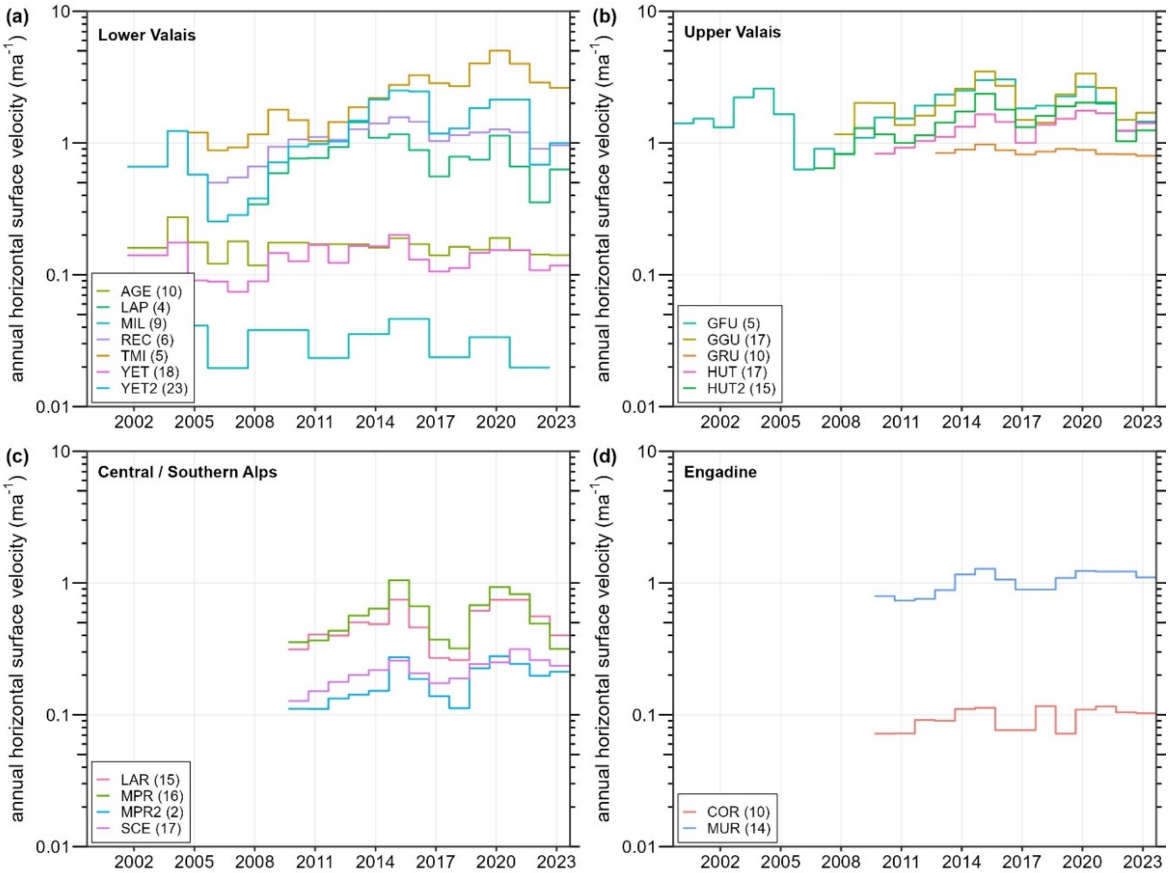

Figure 5.2. Pattern of horizontal surface velocities of 18 rock glacier lobes in the Swiss Alps, divided into four topo-climatic regions. The number of reference points for each site is indicated in brackets next to the site abbreviations (full site names can be found in Table A.1).

The observed regionally different velocity evolution is consistent with the different snow conditions in winter 2023 (see Chapter 2). The later onset of the snow cover and lower snow depths in the eastern, central, and southern parts of the Alps enabled more pronounced cooling of the ground compared to the western part.

Despite regional differences and variable landform size, morphology, and velocity range, a coherent evolution of rock glacier velocity can be identified in the Swiss Alps (Figure 5.3a). Since 2000, velocities have generally increased with marked inter-annual variability (velocity decreases were observed in 2004–2006, 2016–2018 and 2021-2022) due to varying meteorological conditions. Observed rates of increase are highest since 2010 and maximum velocities were recorded in 2015 and/or 2020 depending on the site. Similar rock glacier velocity patterns have been reported in the French, Italian and Austrian Alps (Kellerer-Pirklbauer et al. 2024).

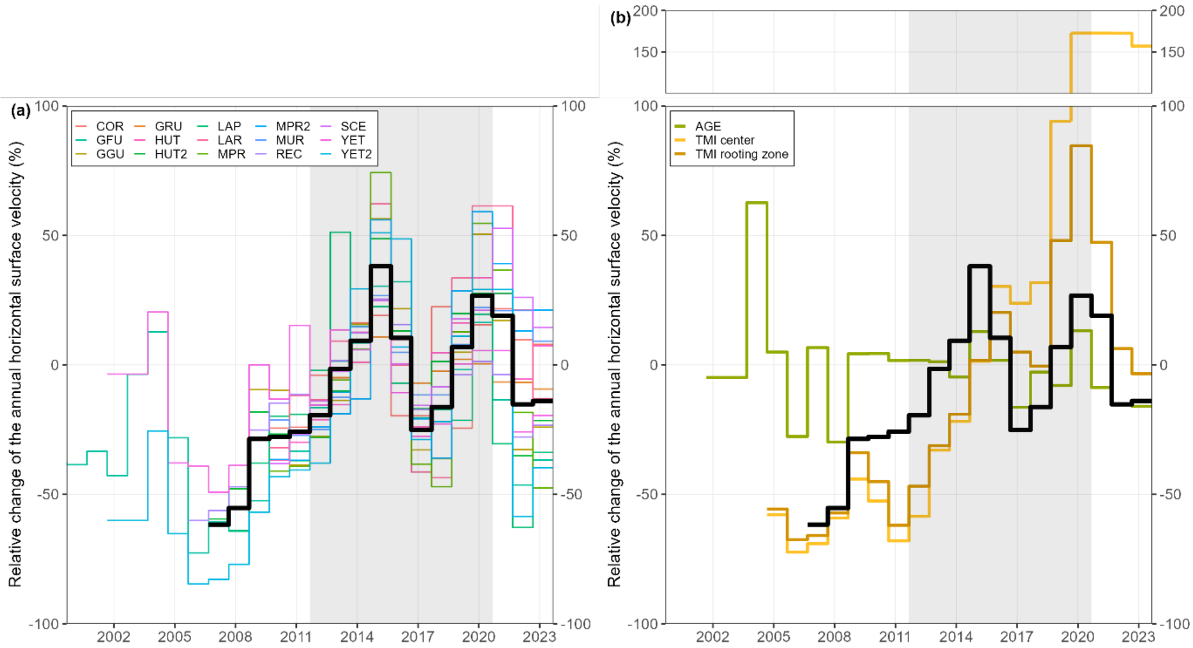

Figure 5.3. Mean annual horizontal surface velocity derived from terrestrial geodetic surveys relative to the reference period 2011–2020 (grey area). The black line represents the average of all measured sites (excluding Tsarmine (TMI) and Aget (AGE)). (a) 15 monitored rock glacier lobes (for site abbreviations see Table A.1). (b)Two atypical rock glaciers (not that TMI is divided into two separate 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) has been accelerating more strongly, especially in its central part while rock glacier Aget (AGE) has been decelerating since the start of the measurements (Figures 5.3b). These contrasting kinematics are also interpreted as a response to climate warming: a deceleration typically indicates in-situ permafrost degradation (i.e., thinning of the permafrost body above the shear horizon and/or increased friction at the shear horizon), whereas an exceptional acceleration points to an ongoing destabilization (see Roer et al. 2008). In both cases, the site-specific mechanisms controlling the rock glacier dynamics become dominant over climate effects for the inter-annual variations in rock glacier velocity. 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 a singular acceleration since 2013 (Figure 5.3b upper panel). Scarps developed between the two different kinematic units due to the extension of the moving mass, which exceeds 60 m between both sections until 2023. The peak activity seems to have been reached in 2021 in the lowermost unit with annual velocities of more than 16 m/y. The velocity will undoubtedly decrease in the coming few years.

5.2 Seasonal rock glacier velocity

Within the PERMOS network, permanent GNSS devices are installed on 8 rock glaciers and 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 m a^{-1}) must 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 to exclude such short-term variations, positions are filtered and aggregated with a 30-days moving window.

Figure 5.4 shows the seasonal evolution of surface velocities for two rock glaciers: Gemmi (GFU, Upper Valais) and Grosses Gufer (GGU, Upper Valais). A typical seasonal pattern can be observed at both 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 iii) 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. The velocity decrease over the winter is partly depending on the intensity of the ground surface cooling.

At both sites, the velocity follows a typical seasonal pattern throughout the hydrological year 2023, with a slightly smaller amplitude than in the previous year. The winter velocity decrease was less marked and the acceleration following the snow melt period was in the same range as in the hydrological year 2022. At Grosses Gufer and Gemmi the end of summer peak was not yet reached in on 1st October 2023, but the velocities were around the same level as in October 2022 yielding slightly faster annual average in 2023 (dashed lines).

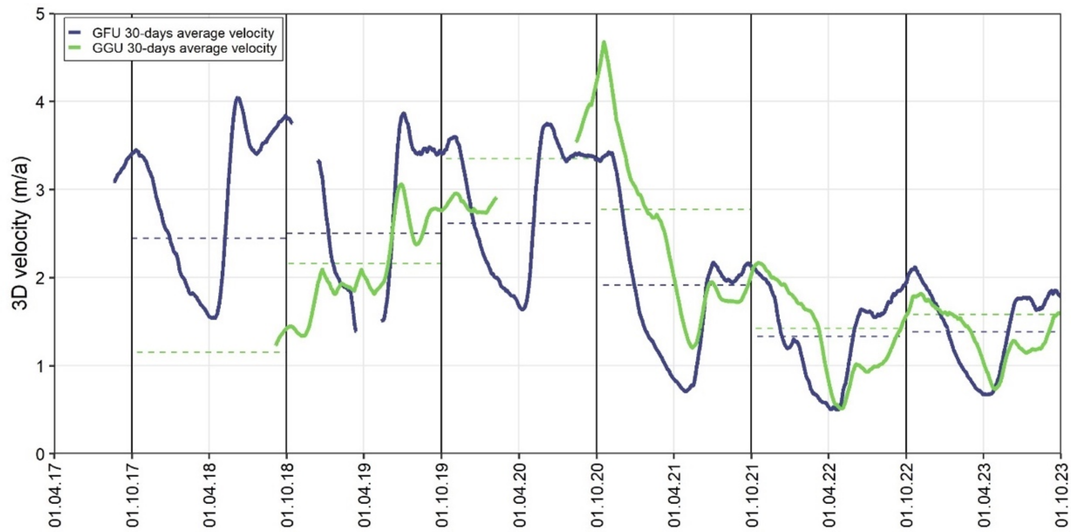

Figure 5.4. Evolution of the seasonal 3D surface velocity at the Gemmi (purple) and Grosses Gufer (green) rock glaciers. The velocities are computed over 30-day periods. The dotted lines represent the annual surface velocity measured by TGS at the nearest boulder.

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 pattern of continued warming and degradation of permafrost in the Swiss Alps since the start of the measurements. This general trend can be overlaid by inter-annual variations in response to annual meteorological conditions, particularly the timing and depth of the snow cover and summer air temperatures.

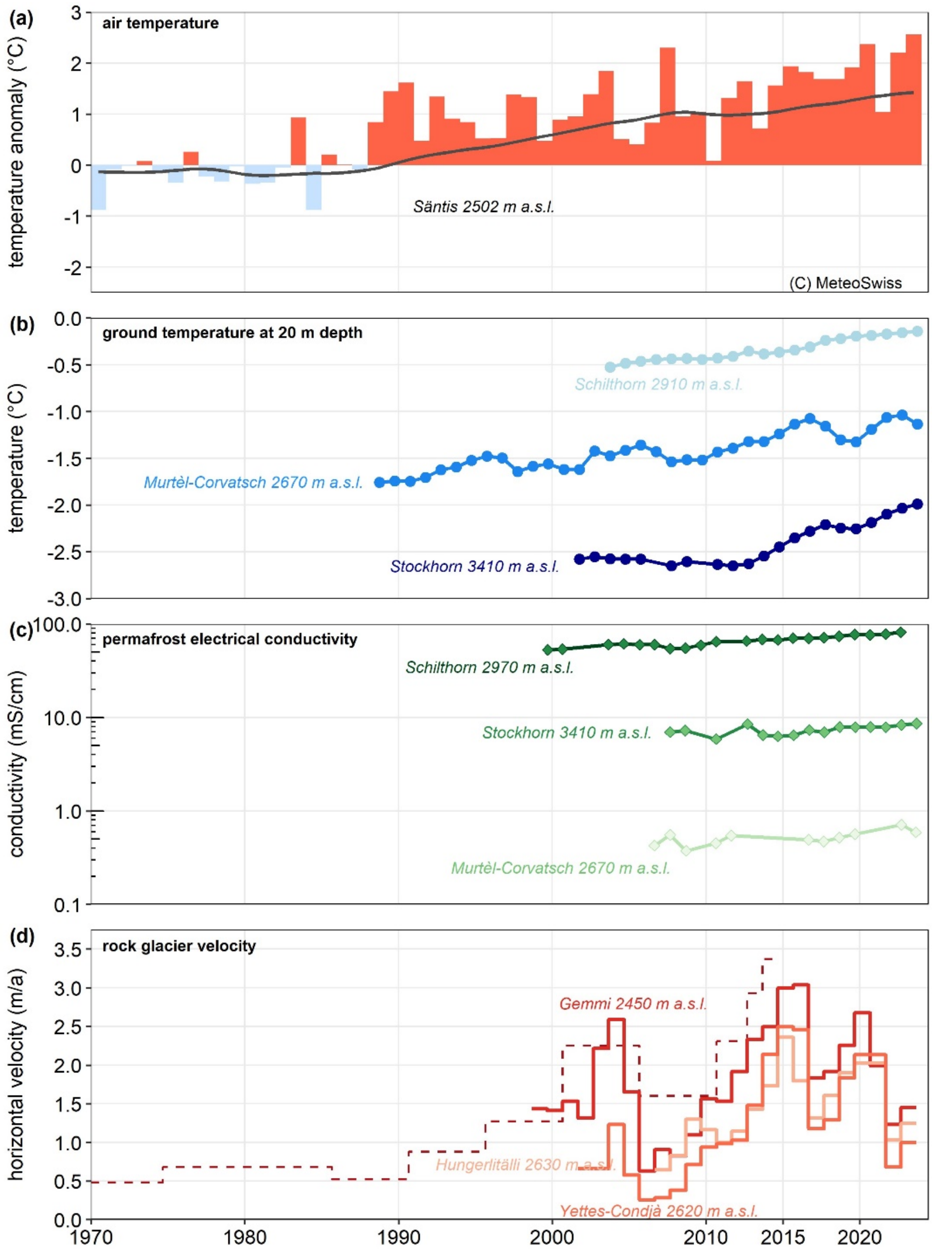

Figure 6.1. Evolution of the three observation elements of PERMOS: annual mean permafrost temperatures at 20 m depth (b), permafrost electrical conductivity (c), and rock glacier creep velocity (d). The dashed red line represents the horizontal surface velocity for Gemmi and is obtained by aerial photogrammetry. The data are compared to long-term air temperature anomaly (1961-1990 reference period) by MeteoSwiss (a).

The air temperature during the hydrological year 2023 was 1.9°C above the long-term mean 1981–2010. The year 2023 was the warmest hydrological year (and the second warmest calendar year) since the start of the measurements in 1864. It was characterized by a very snow poor winter with below average snow heights, followed by a cold and wet spring and a warm summer and autumn. The weather and climate conditions lead to the following permafrost conditions in the Swiss Alps during the hydrological year 2023 (Figure 6.1):

- Compared to previous years, ground surface temperatures remained at high levels. Record running mean annual ground surface temperatures were reached in early 2023 because of the extremely warm atmospheric conditions in summer/autumn 2022.
- Consistently high ALT were observed in 2023 with record thicknesses reached in 5 boreholes. The ALT at Schilthorn further increased reaching a depth of more than 13 meters.
- Permafrost temperatures in 2023 mostly increased slightly by a few tenths of degrees Celsius at 10 m depth at most sites but are below the maximum values recorded in 2020 or 2021. A new record high value was reached at Stockhorn. In contrast, most rock glaciers exhibited a slight decrease in permafrost temperature at 10 and 20 m depth due to the snow-poor winters 2022 and 2023.
- Permafrost electrical resistivities continued to decrease at the high-elevation bedrock site Stockhorn whereas they slightly increased at the Attelas talus slope and Murtèl-Corvatsch rock glacier.
- Compared to 2022, a slight decrease of rock glacier velocity was measured in the Central/Southern Alps and Engadine (–21% and –7%), whereas rock glacier velocities in the Lower and Upper Valais increased slightly (+16% and +9%). The regionally variable signal mostly results from varying snow conditions and consecutive ground cooling intensity in winter 2023.

Overall, the permafrost conditions during the hydrological year 2023 were characterized by warm conditions at the surface and in the uppermost metres. At greater depth, permafrost temperatures increased slightly at 10 m depth and remained at or close to the maximum at 20 m depth for most sites. Most rock glaciers experienced a slight temperature decrease at depth, which was especially marked in the Eastern part of the Swiss Alps and is consistent with the electrical resistivity and rock glacier velocity observations.

Acknowledgements

The Swiss Permafrot Monitoring Network is financially supported by MeteoSwiss, in the framework of GCOS Switzerland, the Federal Office for the Environment FOEN and the Swiss Academy of Sciences SCNAT. The fieldwork and data preprocessing were performed by the seven PERMOS partner institutions: The Swiss Federal Institute of Technology (ETH Zurich) through their Laboratories of Hydraulics, Hydrology and Glaciology (VAW), the WSL Institute for Snow and Avalanche Research SLF, the University of Applied Sciences and Arts of Southern Switzerland (SUPSI) through their Institute of Earth Sciences, the University of Lausanne through the Institute of Earth Surface Dynamics, the University of Innsbruck through the Institute of Informatics, and the Geography Departments of the Universities of Fribourg and Zurich. The in-kind contribution of the partner institutions as well as the personal commitment of PERMOS members are indispensable for the operation of the PERMOS Network.

References

Cicoira, A., Weber, S., Biri, A., Buchli, B., Delaloye, R., Da Forno, R., Gärtner-Roer, I., Gruber, S., Gsell, T., Hasler, A., Lim, R., Limpach, P., Mayoraz, R., Meyer, M., Noetzli, J., Phillips, M., Pointner, E., Raetzo, H., Scapozza, C., Strozzi, T., Thiele, L., Vieli, A., Vonder Mühll, D., Wirz, V. and Beutel, J. 2022. In situ observations of the Swiss periglacial environment using GNSS instruments. Earth System Science Data, 14(11), 5061–5091. https://doi.org/10.5194/essd-14-5061-2022

Cicoira, A., Marcer, M., Gärtner-Roer, I., Bodin, X., Arenson, L. U., and Vieli, A. 2020. A general theory of rock glacier creep based on in-situ and remote sensing observations. Permafrost and Periglacial Processes, 32(1), 139–153. https://doi.org/10.1002/ppp.2090

Hoelzle, M., Hauck, C., Mathys, T., Noetzli, J., Pellet, C. and Scherler, M. 2022. Long-term energy balance measurements at three different mountain permafrost sites in the Swiss Alps. Earth System Science Data, 14(4), 1531–1547. https://doi.org/10.5194/essd-14-1531-2022

Kellerer-Pirklbauer, A., Bodin, X., Delaloye, R., Lambiel, C., Gärtner-Roer, I., Bonnefoy-Demongeot, M., Carturan, L., Damm, B., Eulenstein, J., Fischer, A., Hartl, L., Ikeda, A., Kaufmann, V., Krainer, K., Matsuoka, N., Cella, U. M. D., Noetzli, J., Seppi, R., Scapozza, C., Schoeneich, P., Stocker-Waldhuber, M., Thibert, E. and Zumiani, M. 2024. Acceleration and interannual variability of creep rates in mountain permafrost landforms (rock glacier velocities) in the European Alps in 1995–2022. Environmental Research Letters, 19(3), 034022. https://doi.org/10.1088/1748-9326/ad25a4

MeteoSwiss 2024. Klimabulletin Jahr 2023. 16 pp., Zürich.

MeteoSwiss 2023. Klimabulletin Jahr 2022. 13 pp, Zürich

Mollaret, C., Hilbich, C., Pellet, C., Flores-Orozco, A., Delaloye, R., and Hauck, C. 2019. Mountain permafrost degradation documented through a network of permanent electrical resistivity tomography sites. The Cryosphere, 13(10), 2557–2578. https://doi.org/10.5194/tc-13-2557-2019.

Noetzli, J., Arenson, L., Bast, A., Delaloye, R. Farinotti, D., Gubler, H.-U, Gruber, S., Haeberli, W., Hasler, A., Hauck, C., Hiller, M., Hoelzle, M., Pellet, C., Springman, S., Vonder Muehll D., and Phillips, M. 2021. Best practice for measuring permafrost temperature in boreholes based on the experience in the Swiss Alps. Frontiers in Earth Science, https://doi: 10.3389/feart.2021.607875.

PERMOS 2019. Permafrost in Switzerland 2014/2015 to 2017/2018. Noetzli, J., Pellet, C. and Staub, B. (eds.), Glaciological Report Permafrost No. 16–19 of the Cryospheric Commission of the Swiss Academy of Sciences, 104 pp, https://doi.org/10.13093/permos-rep-2019-16-19.

Pielmeier C., Zweifel B., Techel F., Marty C., Grüter S. and Stucki T. 2024: Schnee und Lawinen in den Schweizer Alpen. Hydrologisches Jahr 2022/23. WSL Ber. 145: 84 pp. doi.org/10.55419/wsl:36046

Roer, I., Haeberli, W., Avian, M., Kaufmann, V., Delaloye, R., Lambiel, C., and Kääb, A. 2008. Observations and considerations on destabilizing active rock glaciers in the European Alps. Proceedings of the 9th International Conference on Permafrost, 1505–1510. https://doi.org/info:doi/10.5167/uzh-6082

Staub, B., Lambiel, C., and Delaloye, R. 2016. Rock glacier creep as a thermally-driven phenomenon: A decade of inter-annual observation from the Swiss Alps. In Günther, F. & Morgenstern, A. (eds.) XI International Conference on Permafrost - Book of Abstracts, 20-24 June 2019, Potsdam, Germany, 96–97. https://doi.org/10.2312/GFZ.LIS.2016.001

Staub, B., Hasler, A., Noetzli, J. and Delaloye, R. 2017. Gap filling algorithm for ground surface temperature data measured in permafrost and periglacial environments. Permafrost and Periglacial Processes, https://doi.org/10.1002/ppp.1913.

Streletskiy, D., Noetzli, J., Smith, S.L., Vieira, G., Schoeneich, P., Hrbacek, F., and Irrgang, A. M. 2021. Strategy and Implementation Plan for the Global Terrestrial Network for Permafrost (GTN-P) 2021-2024, https://doi:10.5281/ZENODO.6075468.

Wirz, V., Beutel, J., Gruber, S., Gubler, S., and Purves, R. S. 2014. Estimating velocity from noisy GPS data for investigating the temporal variability of slope movements. Natural Hazards and Earth System Sciences, 14(9), 2503–2520. https://doi.org/10.5194/nhess-14-2503-2014.

WMO 2017. WMO guidelines on the calculation of climate normals, World Meteorological Organization WMO, No. 1203, 18 pp. Geneva, Switzerland.

WMO 2022. The 2022 GCOS ECV Requirements. World Meteorological Organization (WMO), United Nations Educational, Scientific and Cultural Organization, Intergovernmental Oceanographic Commission, United Nations Environment Programme, International Science Council (ISC), GCOS No. 245, 261 pp. Geneva, Switzerland.

Appendix

Table A.1. Location and characteristics of the PERMOS sites together with the type of measurement obtained at the site: BHT means borehole temperature, GST is ground surface temperature, ERT is Electrical Resistivity Tomography, TGS is Terrestrial Geodetic Survey. X and Y denote CH1903 coordinates, and Z is the elevation in m asl.

Name	Site abbr.	Regions	Morphology	X	Y	Z	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 glaciers	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		