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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 at http://permos.ch/data.html. This report is based on the PERMOS data set doi:10.13093/permos-2022-01.

Cover page

Rock glacier tongue in the Val d'Err (GR) below the Piz Bleis Marscha (3128 m asl., in the clouds). Photo: A. Hasler, 2021.

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. A general trend of permafrost warming and degradation in the Swiss Alps is documented by more than 20 years of data, which also show some spatial variability related to site characteristics and shorter-term variations due to meteorological conditions.

The mean annual air temperature in the hydrological year 2021 (October 2020 to September 2021) was 0.3 °C above the long-term mean 1981–2010, and it was the lowest since 2013. The hydrological year 2021 was characterized by a mild winter with a long-lasting snow cover, a cold spring, a wet summer and a dry and sunny autumn.

As a result of the meteorological conditions, the mean annual ground surface temperatures (MAGST) in the hydrological year 2021 decreased 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 lower than in the hydrological year 2020.

The cooler conditions at the surface resulted in heterogeneous active layer thicknesses (ALT) in 2021 with greater ALT than 2020 at 4 sites and lower ALT at 5 sites. For two sites, new record values were registered. The same heterogeneous picture is observed for the permafrost temperatures at 10 m depth: they slightly decreased, remained relatively stable, or slightly increased. At greater depth, that is at 20 m depth, permafrost temperatures react delayed and filtered to the changes at the surface. Here, permafrost temperatures have not (yet) been affected by the colder surface conditions and continued to increase at all sites. At many sites they even reached new record temperatures in 2021.

The permafrost resistivities measured in 2021 again point to different conditions between the uppermost meters of the ground and larger depths. Resistivities slightly increased in talus slopes compared to 2020, indicating the presence of more ice and less unfrozen water. At bedrock sites, which were less affected by winter cooling, resistivities decreased, indicating less ice and more unfrozen water.

The kinematics of rock glaciers indirectly reflect the thermal conditions of the permafrost as the changes in rock glacier velocities follow the permafrost temperatures: when permafrost temperatures increase, rock glaciers generally accelerate. In 2021, rock glaciers decelerated with an average velocity decrease of –8.5% compared to 2020 and a maximum decrease of –44%.

Overall, the hydrological year 2021 was characterized by colder conditions at the surface and in the uppermost metres of the ground compared to the previous year (lower ground surface temperature, shallower ALT at several sites, and lower creep velocities) as well as by a continued increase of permafrost temperatures at larger depths.

Contents

1 Introduction

The Swiss Permafrost Monitoring Network PERMOS documents the state and changes of permafrost in the Swiss Alps based on field measurements. The most recent 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 evolution. This report covers the hydrological year 2021, which includes the one year period from 1 October 2020 to 30 September 2021.

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

The monitoring setup of PERMOS is based on field measurements of a set of complementing variables, which is consistent with the ECV «Permafrost»: 1) ground temperatures at the surface and at depth, 2) permafrost resistivity to assess changes in ground ice content, and 3) rock glacier velocities. Active layer thickness is derived from temperature time series measured at multiple depths in boreholes. In addition, meteorological data are obtained at borehole sites, and mass movements (i.e., rock falls and rock avalanches) originating from permafrost areas are documented.

The monitoring setup follows a landform-based approach because differences in the permafrost evolution related to topography, snow regime, and ground ice content are considered more important in a small country than those due to regional climate conditions (PERMOS 2019, Noetzli et al. 2021). The PERMOS network remained unchanged in 2021 compared to the previous year and includes 27 field

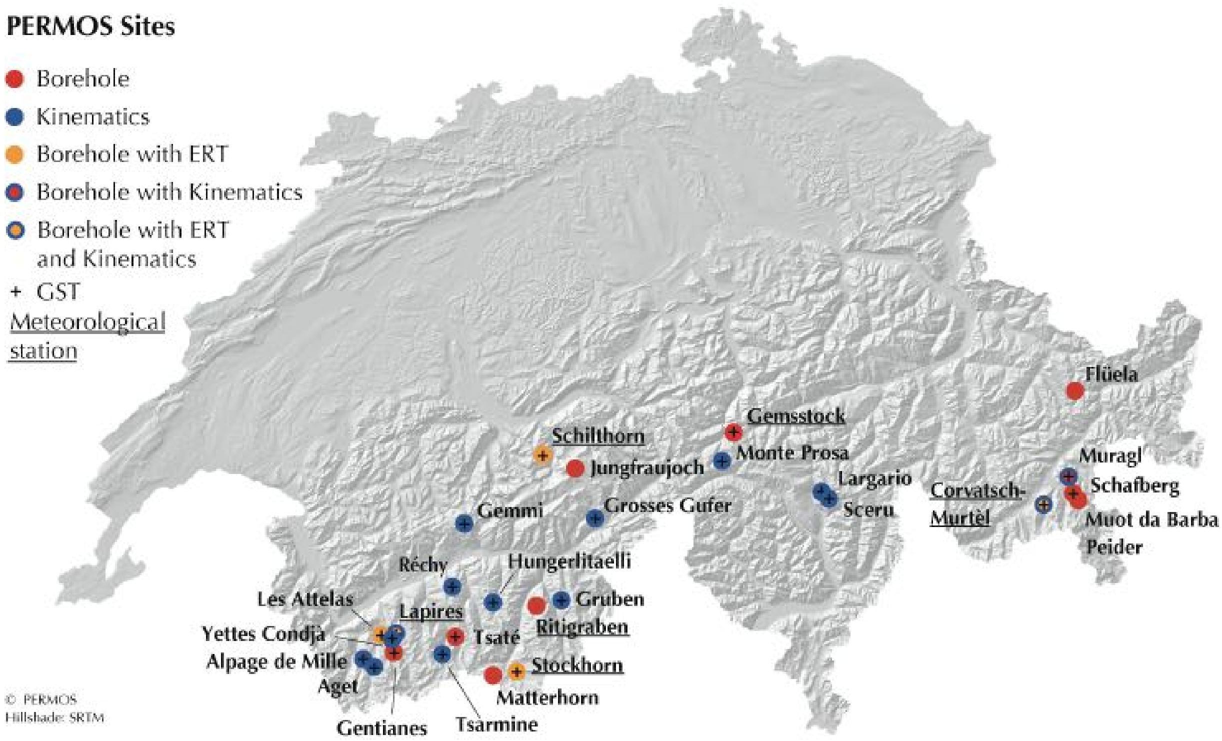

Figure 1.1: PERMOS field sites and measured variables in 2021.

sites (Figure 1.1, Table A.1): Ground temperatures are measured at 15 sites in 29 boreholes (1–4 boreholes per site) of 14–100 m depth. Six of these sites are equipped with automatic weather stations (cf. Hoelzle et al. 2021) and for 5 sites, geophysical surveys are conducted annually. Rock glacier velocity 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. Ground surface temperature (GST) is measured at 22 PERMOS sites with a total of 236 miniature temperature 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). Six academic partner institutions (ETH Zurich, Universities of Fribourg, 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 SLF) operates the network, implements the monitoring strategy, manages and analyses the data, and is in charge of publishing and communicating results. Two standing committees advise and supervise the network, politically and financially (PERMOS Steering Committee) as well as scientifically (PERMOS Scientific Committee).

2 Weather and climate

Air temperature and snow cover are the meteorological variables with the main influence on the seasonal and inter-annual variations of the thermal regime of mountain permafrost. Changes in air temperature drive changes at the ground surface in periods with little or no snow, and all year round for very steep bedrock slopes where no thick snow cover develops during winter. An early snow cover conserves the heat in the ground while a long-lasting snow cover insulates the ground from increasing air temperatures in early summer. Therefore, the onset of an insulating snow cover and the time when the ground surface becomes snow free are relevant for permafrost evolution. The weather and climate information presented is based on MeteoSwiss (2021, 2022) and Zweifel et al. (2021).

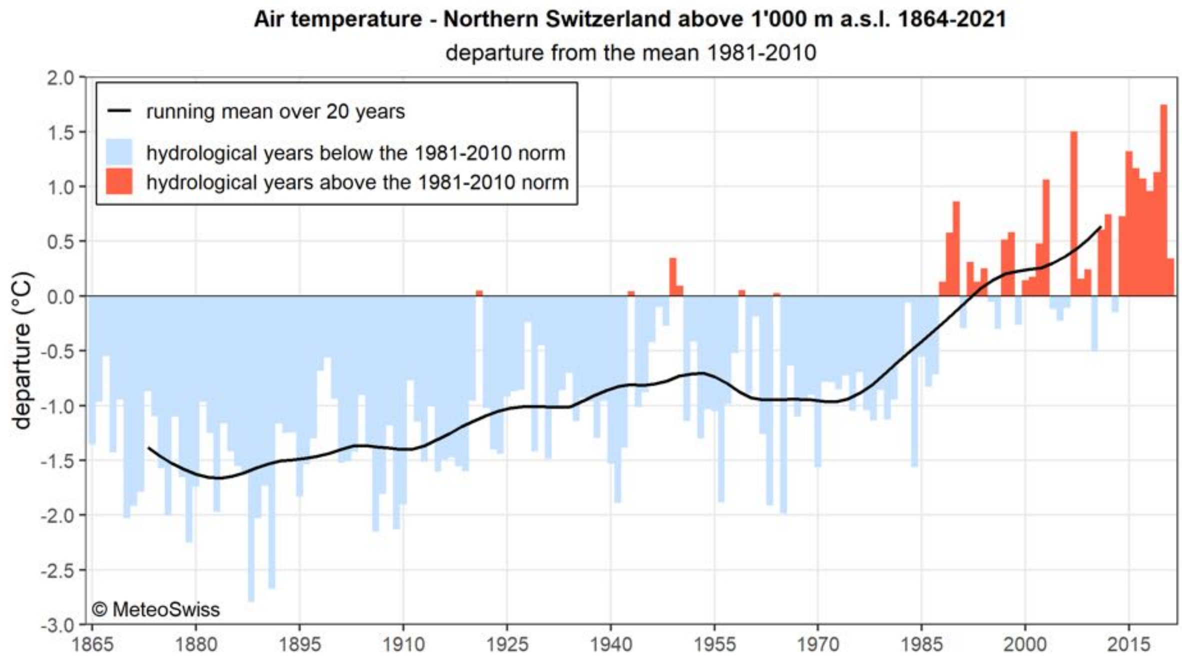

Figure 2.1: Air temperature deviation from the 1981–2010 norm based on homogenized data series for Swiss stations above 1000 m asl. and for hydrological years. Adapted from MeteoSwiss (2022).

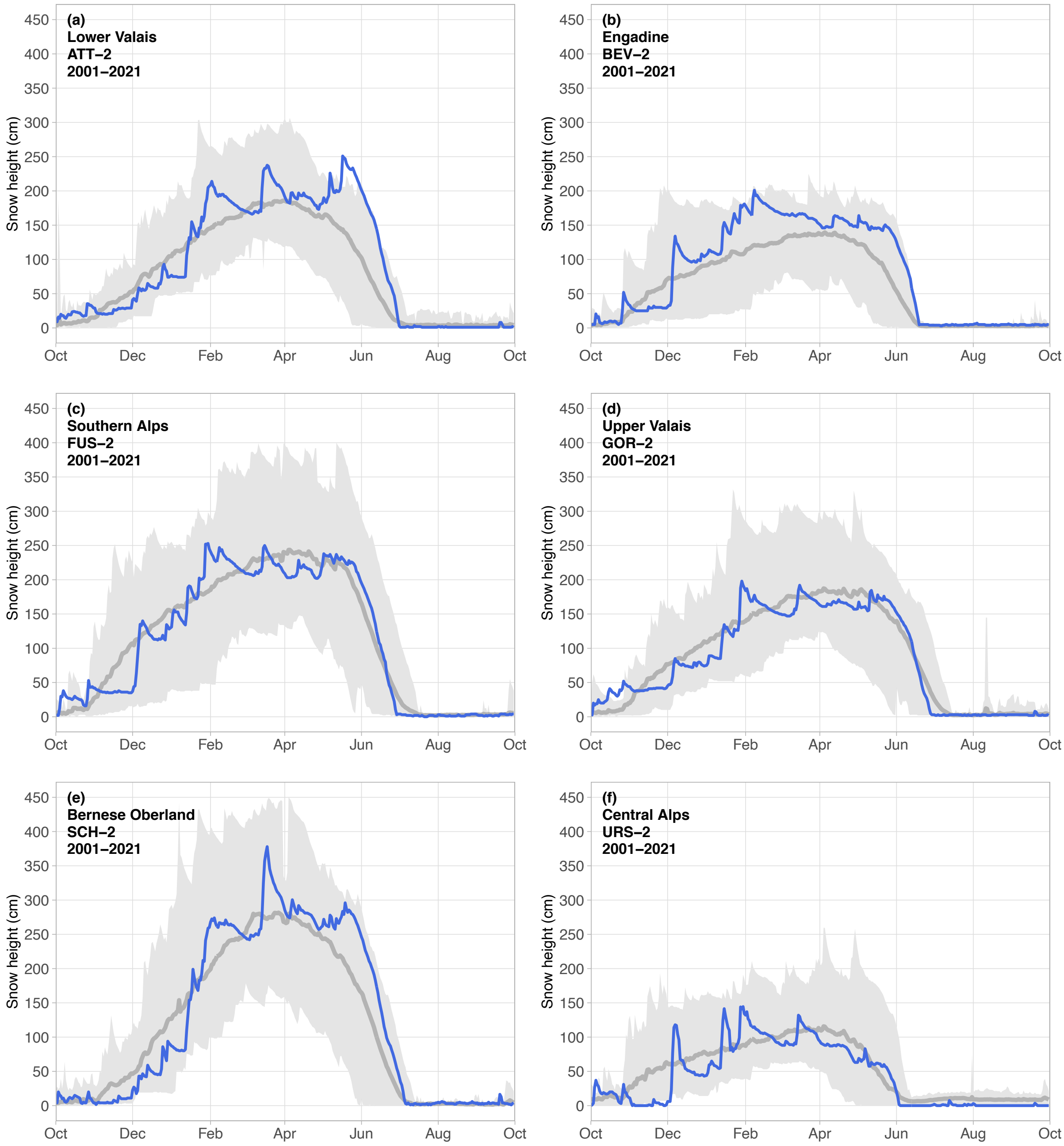

Figure 2.2: Snow height at six IMIS stations during winter 2021 (blue line) compared to the mean (thick grey line) and range (light grey shaded area) of the 20-year period 2001–2021. Data were corrected for outliers and aggregated to daily median values. The stations represent different regions in the Swiss Alps: a) Lower Valais, b) Engadine, c) Southern Alps, d) Upper Valais, e) Bernese Oberland, and f) Central Alps. Data source: IMIS/SLF.

Winter 2021 was warmer than the average 1981–2010 with above average snow depths in Grisons and average snow depths in the rest of Switzerland. At higher elevations, the winter started with intense snow fall in October 2020 on both sides of the Alps (Figure 2.2). It was followed by a dry November. Air temperatures in October and January were below the average, and above average in November and December. Heavy snowfall mainly occurred in early December 2020, and in mid- and late January 2021. After a dry and very mild February, winter returned in mid-March with abundant snowfall. While air temperatures in March were average, the low temperatures in April and

May 2021 led to the coldest spring in over 30 years, which was 1.1 °C colder than the average 1981–2010. Snowmelt was delayed by about 1–2 weeks.

Summer 2021 was colder than the previous 6 summers and one of the wettest on record, locally with precipitation sums that were 160% above the norm. Air temperature was close to the 30-year average 1981–2010 with +0.5 °C. Temperatures were above average in June and below average in July and August. September 2021 was dry and sunny, with temperatures slightly above the long-term mean.

Overall, the mean annual air temperature (MAAT) of the hydrological year 2021 was 0.3 °C higher than the 30-year average 1981–2010 (Figure 2.1). The hydrological year 2021 was the coldest since 2013 and characterized by a warm winter with a long-lasting snow cover, a cold spring, a wet summer, and a dry and sunny autumn.

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 the ECV permafrost. Within PERMOS, continuous ground temperatures are automatically logged in boreholes of 14–100 m depth (Noetzli et al. 2021). Borehole measurements are additionally used to determine the ALT – the layer of ground that freezes and thaws annually. The point information from boreholes is complemented by spatially distributed temperature measurements at the ground surface.

3.1 Ground surface temperatures

Ground surface temperatures result from the energy balance at the ground surface and their changes subsequently penetrate to depth. They are continuously recorded at 22 sites with 5–15 miniature temperature data loggers per site (236 in total). The data loggers are distributed close to boreholes or a network of GPS points. They are buried a few decimetres below the ground surface 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 data provide information about the thermal conditions at the ground surface and their spatial variability.

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

The mean annual ground surface temperature (MAGST) was about 1 °C lower during the hydrological year 2021 than in the previous year and below the average 2012–2015 (Figure 3.1). For the sites with long-time series, MAGST was below the 20-year average 2001–2020. Although GST data were collected for all sites in summer/autumn 2021, MAGST could only be calculated for half of the sites (when allowing a gap of 4 days at the end of September), all talus slope and rock glacier sites. For the other sites (including all bedrock sites), field work was done before end of September and no mean for the hydrological year 2021 could be calculated yet.

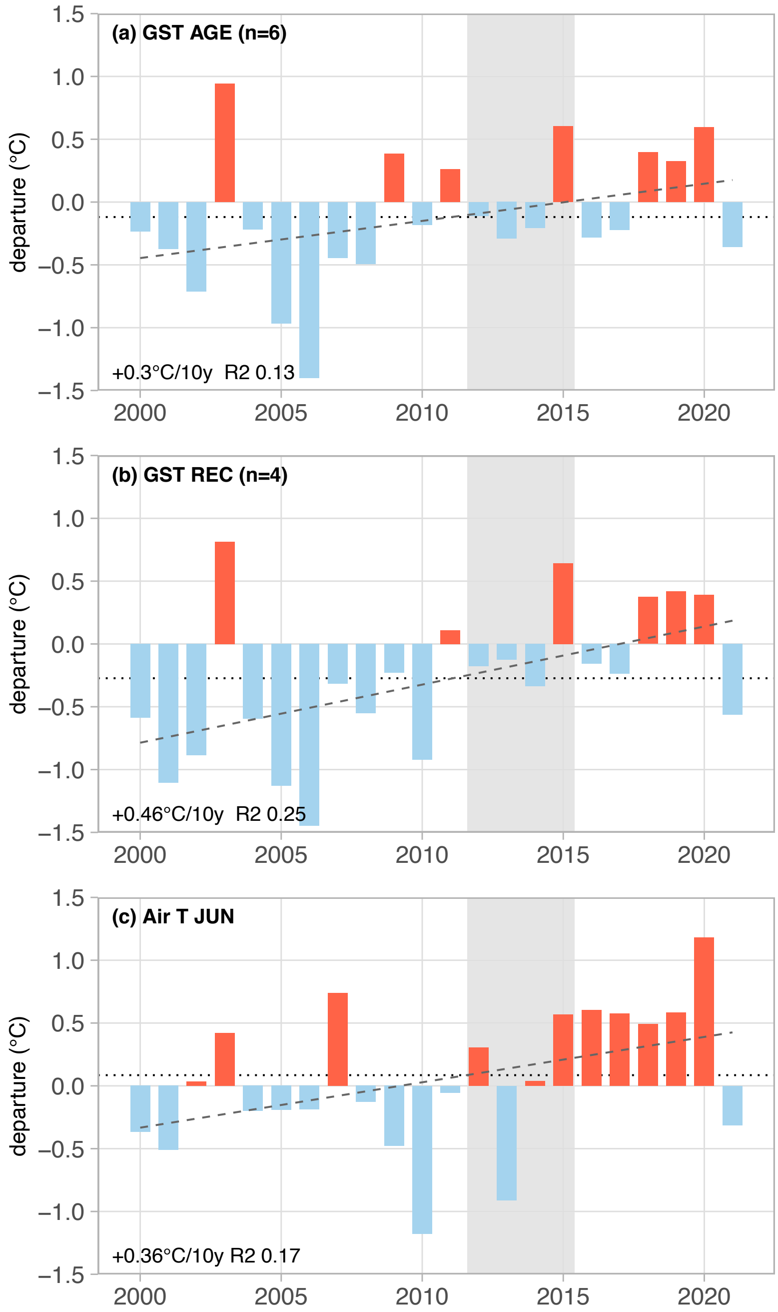

Figure 3.1: Deviation of the mean annual ground surface temperature from the 2012–2015 average (the reference period used for rock glacier velocities, hydrological years) for two rock glacier sites with time series >20 years: Aget (VS, a) and Réchy Becs de Bosson (b). At the bottom (c), the comparison to the air temperature anomaly at Jungfraujoch is shown (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 entire time series (the slope and goodness of the fit are indicated), the dotted line indicates the mean deviation 2001–2020.

The long-term evolution of GST can be described by a running annual mean (rMAGST, Figure 3.2). The rMAGST continuously remained at a high level above the long-term average since the temporary cooling in 2016/2017 (see PERMOS 2019). During the hydrological year 2021, rMAGST significantly decreased at all sites and for all types of terrain as a result of the meteorological conditions.

The site mean of the MAGST was above 0 °C at most of the sites since the start of the time series. 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: that is, 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 because of non-conductive heat transport in the active layer. Further, the permafrost conditions at depth are not in thermal equilibrium with the current climatic setting.

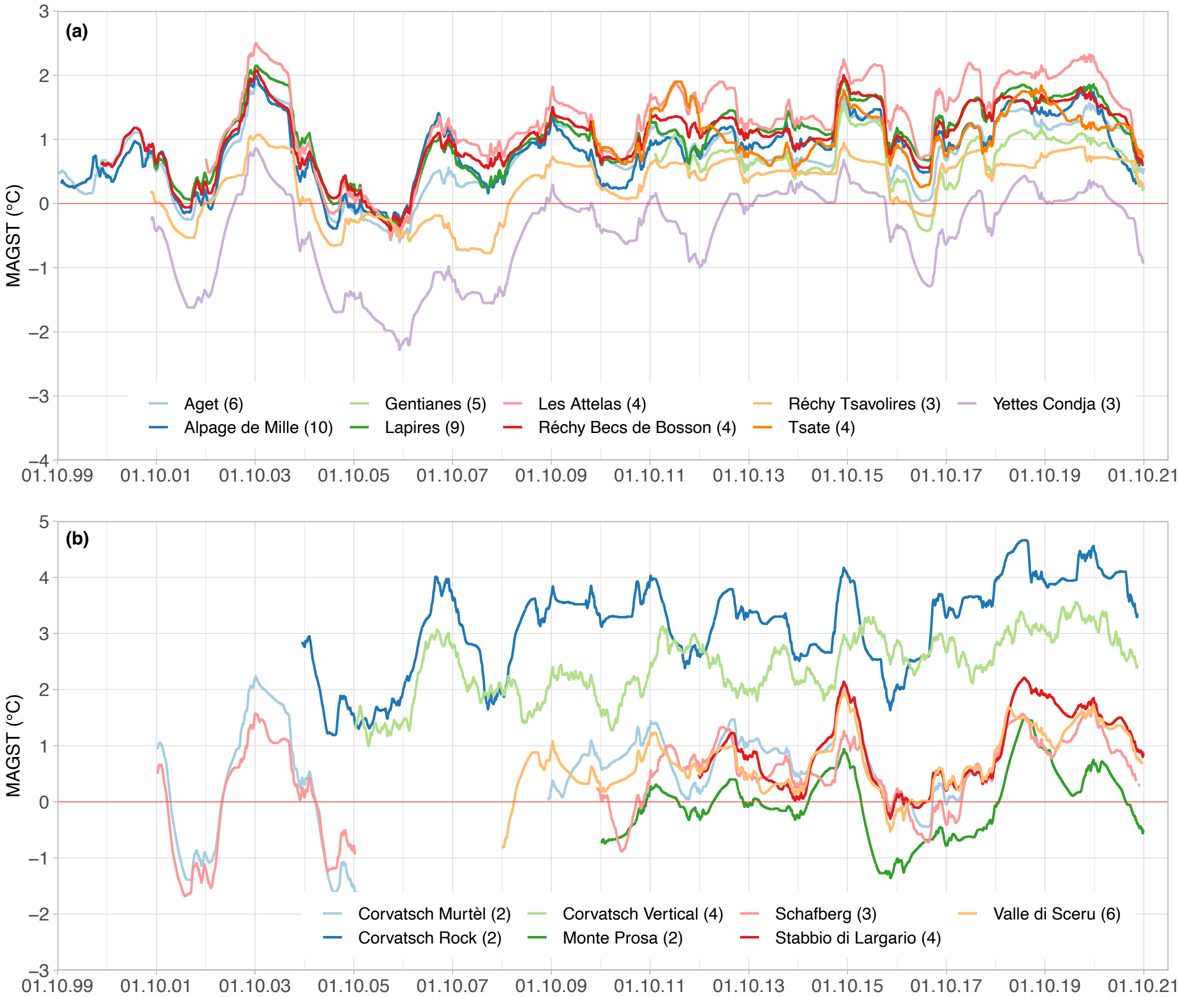

Figure 3.2: Running mean annual ground surface temperature (MAGST) for sites in the Lower Valais region (a) and in the East and South of the Swiss Alps (b). Corvatsch Rock and Corvatsch Vertical are measured in flat and steep bedrock. All other sites are on debris covered landforms (rock glaciers and talus slopes). Series depict site averages (the number of loggers used is given in brackets) and are smoothed with running annual means. Daily GST time series were gap-filled following Staub et al. (2017).

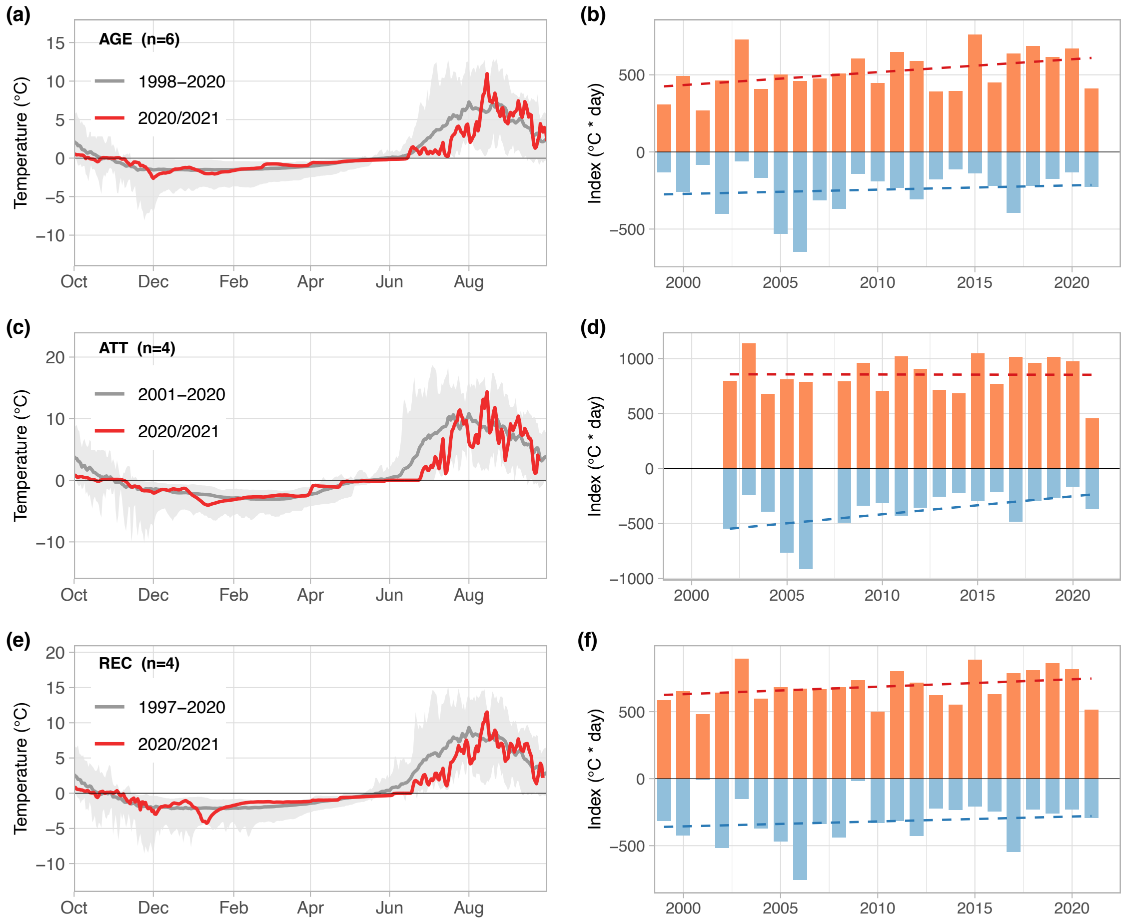

Figure 3.3: Daily mean ground surface temperatures during the hydrological year 2021 (red lines) compared to the previous ca. 20 years (grey shades, left) and Ground Freezing and Thawing Indices (GFI and GTI, right) in unconsolidated material (rock glacier Aget, talus slope Les Attelas, rock glacier Réchy Bec de Bosson). Series depict site averages (the number of loggers used is given in brackets). Dotted lines in the right panels indicate the linear trend since the start of the measurements.

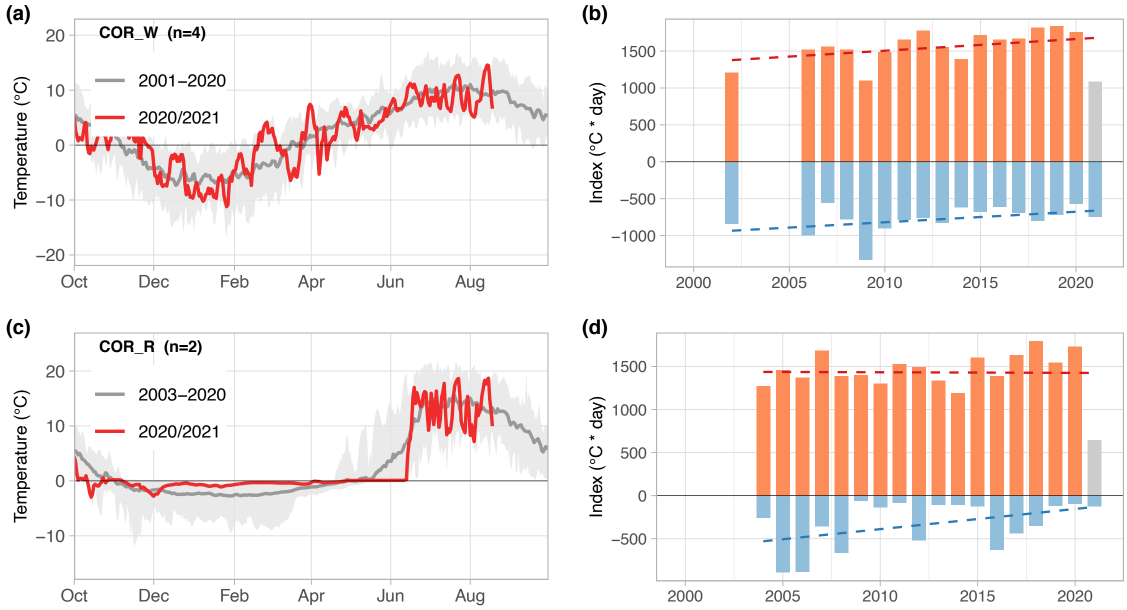

Figure 3.4: Same as Figure 3.3 for steep (top) and flat (bottom) bedrock on Corvatsch (GR). GTI for 2021 are shown in grey because the available data series end in August 2021.

The Ground Freezing Indices (GFI, defined as the sum of the negative daily temperatures during a hydrological year) for the GST show lower values in the hydrological year 2021 than in the previous three years (Figure 3.3 and 3.4). The Ground Thawing Indices (GTI, defined as the annual sum of positive daily temperatures) can only be determined for sites with data reaching until the end of September 2021. For these sites, GFI is clearly lower than in the previous years as summer 2021 was cooler and wetter.

3.2 Active layer thickness

The maximum penetration of the summer thaw defines the active layer thickness (ALT). It reflects the snow and atmospheric conditions during the current and previous year. ALT is determined by linear interpolation of borehole temperatures using the lowermost sensor in the active layer (>0°C) and the uppermost sensor in the permafrost (≤0°C). However, because the temperature profile in the uppermost meters is typically not linear due to freeze/thaw processes and varying ground characteristics, quantitative changes in ALT should be interpreted with care. Qualitative changes and general trends in the thickness of the active layer are however considered robust.

The ALT could be determined for 16 boreholes at 10 sites for summer/autumn 2021. Four of the values are should be considered a minimum as they are based on time series, which do not completely cover the period when the thaw penetration may reach its maximum depth (which can be at the end of autumn or even the beginning of winter at some sites). No ALT could be determined for boreholes, where data were collected earlier in summer, for boreholes in which no active layer is measured or where sensor failure occurred at the depths required for the calculation.

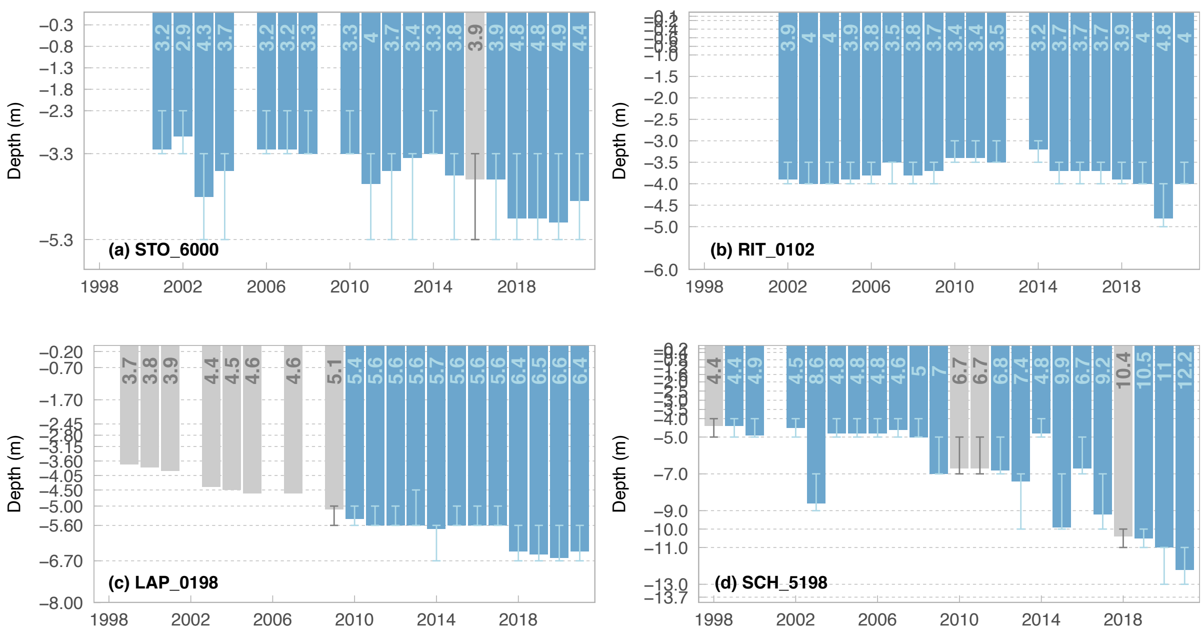

Figure 3.5: Active layer thickness (ALT) derived from borehole temperature data measured on the Stockhorn Plateau (a), in the Ritigraben rock glacier (b), in a talus slope at Lapires (c), and on the summit crest of Schilthorn (d). The uncertainty bars are defined by the thermistors used for the interpolation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

ALT calculated for the hydrological year 2021 were between 2.9 m (Flüela) and 12.1 m (Schilthorn, Figure 3.5). The difference to 2020 ranges between –0.7 m (RIT_0102) and +1.1 m (SCH_5198). For 9 boreholes at 5 sites, ALT in 2021 was smaller than in 2020. For 2 boreholes at 2 sites, ALT remained the same as in 2020, and for 5 boreholes at 3 sites, ALT was greater than 2020. In 2021 ALT even reached new record values for the boreholes SCH_5198 (ALT=12.1 m), SCH_5200 (ALT=11.6 m) and GEN_0102 (ALT=5.9 m). The order of magnitude of the 12 m thaw depth observed in 2021 on Schilthorn (Figure 3.6) in borehole SCH_5198 is confirmed by two boreholes nearby (SCH_5200, ALT=11.6 m, and SCH_5318, ALT=9.6 m). At most sites, the maximum thaw penetration was reached earlier in 2021 than in 2020, i.e., mid-August or later. At Schilthorn, the maximum thaw penetration only occurred in December 2021.

Figure 3.6: The PERMOS instrumentation on Schilthorn is located at nearly 3000 m asl. in the North slope below the summit station. The measurement setup includes 4 boreholes, GST, a meteo station and one ERT profile. Photo: A. Hasler, 2021.

3.3 Permafrost temperatures

Ground temperatures in the uppermost metres react to short-term variations in meteorological conditions. Seasonal variations are measured down to the depth of the zero annual amplitude (DZAA), which is at 15–20 m in the Swiss Alps. Below the DZAA, ground temperatures react with considerable delay to multi-annual trends and indicate climate-related changes. In addition to air temperature, the most important factors influencing permafrost temperature changes are the timing of the winter snow cover (see Chapter 2) and the ground ice content. 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 permafrost changes until the frozen material has thawed entirely, additional measurements sensitive to changes in ground ice and unfrozen water content are required (see Chapter 4).

Continuous permafrost temperatures are recorded at multiple depths in 29 boreholes at 15 sites, which are instrumented with multi-sensor cables and automatic logging, and ideally remote access to the data. Best practices for long-term borehole temperature measurements in mountain permafrost based on the experience of the PERMOS group are described by Noetzli et al. (2021).

During the hydrological year 2021, the mean annual permafrost temperatures (MAPT) at 10 m depth slightly decreased or remained stable compared to the previous year at five borehole sites (e.g., Murtèl-Corvatsch, Ritigraben, Les Attelas, Figure 3.8). On the other hand, MAPT at 10 m depth slightly increased in comparison to the previous year at 7 sites (e.g., Lapires, Schafberg or Gentianes). For the other sites, data do not yet sufficiently cover the reporting period.

At depths around 20 m, the picture is more consistent: The cooler surface conditions have not (yet) affected the thermal conditions at larger depth and the permafrost temperatures continued to increase at all sites. At many sites, MAPT at ca. 20 m depth were close to the previously recorded maximum (e.g., Les Attelas) or even reached new record values (e.g., Gentianes, Murtèl-Corvatsch, Schafberg, Stockhorn).

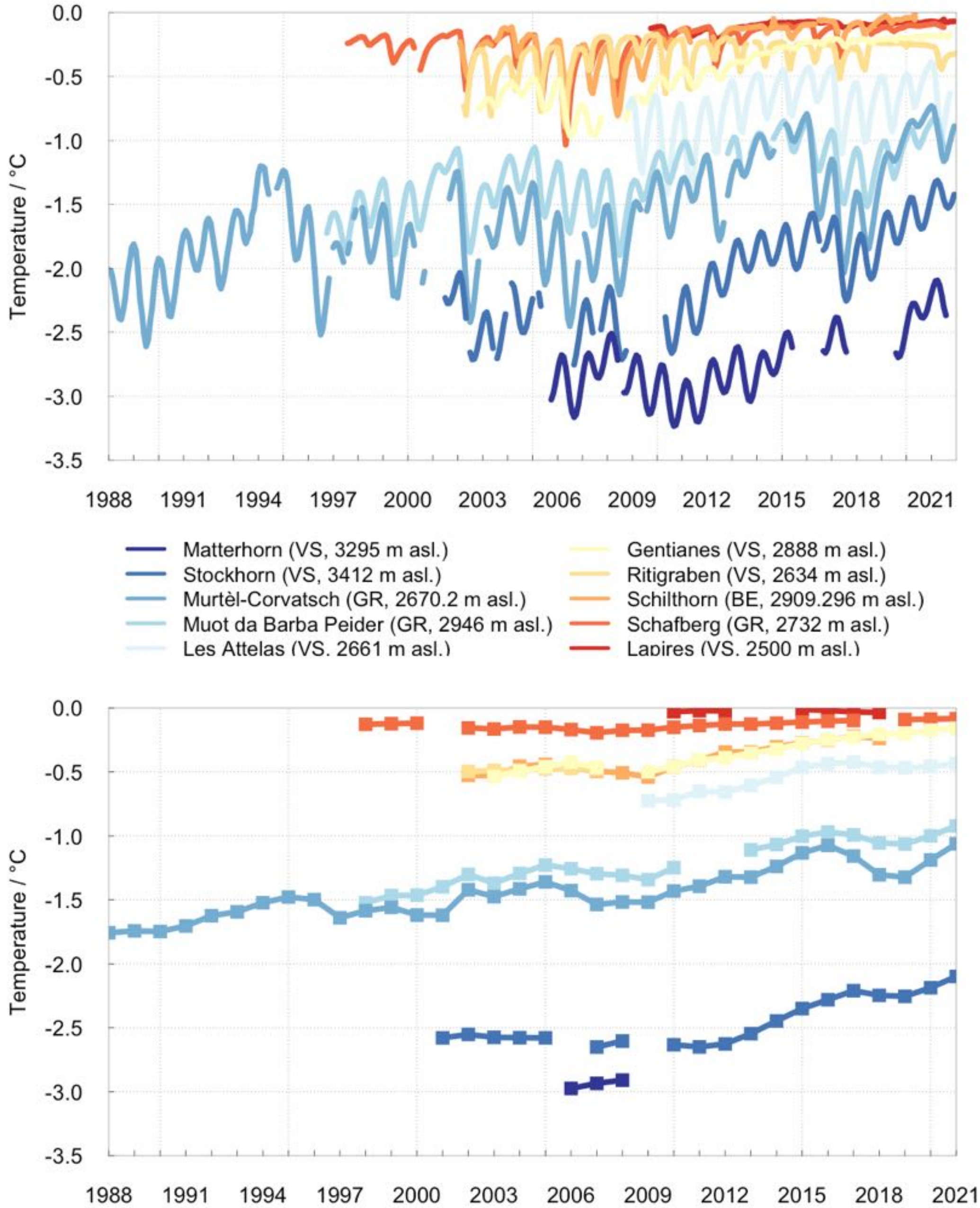

Figure 3.8: Permafrost temperatures measured in selected boreholes at 10 m (a, monthly means) and 20 m depth (b, means of the hydrological year).

4 Electrical resistivities

Geophysical, and especially geoelectrical methods such as Electrical Resistivity Tomography (ERT) provide cost-effective, non-invasive and spatially distributed measurements of ground properties. They have been used for permafrost and ground ice detection and monitoring for decades. The large contrast in electrical resistivity between ice and unfrozen water makes ERT surveys particularly suited to monitor frozen ground. These measurements are an important complement to ground temperatures: Where permafrost is close to 0°C, increased energy input from the ground surface does not result in a significant increase in ground temperature due to the latent heat required for ground ice melt. Instead, it results in ground ice melt, which causes important resistivity changes and is clearly visible using ERT.

Changes in electrical resistivity are observed based on repeated ERT surveys at fixed installed profiles. Decreasing electrical resistivities indicate an increase of the ratio between unfrozen water and ice content. In general, a decrease in resistivity indicates a decrease in the overall ground ice content. Conversely, increasing electrical resistivities indicate an increase of the ground ice content.

The electrical resistivities are repeatedly measured at five borehole sites along fixed installed profiles of 55 to 220 m length and using 48 to 55 permanently installed electrodes (stainless steel rods, Figure 4.1). 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).

The electrical resistivities measured at the different sites span over several orders of magnitudes (Figure 4.2). The lowest resistivities (around 3'000 Ωm) are found at Schilthorn, which is characterized by a weathered bedrock subsurface, low ground ice content and permafrost temperatures close to 0°C. Conversely the highest resistivities (around 300'000 Ωm) are measured on rock glacier Murtèl-Corvatsch, which is characterized by high ground ice content and permafrost temperatures between –1 and –2°C below the DZAA.

To facilitate inter-site comparison and temporal evolution analysis, spatially averaged resistivity values are computed for manually selected representative zones within the permafrost (cf. Figure 4.2). The representative 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). The active layer is excluded where possible to focus on the permafrost and longer-term temporal variations.

Figure 4.1: Electrical Resistivity Tomography (ERT) survey at Stockhorn (VS). Photo: C. Mollaret

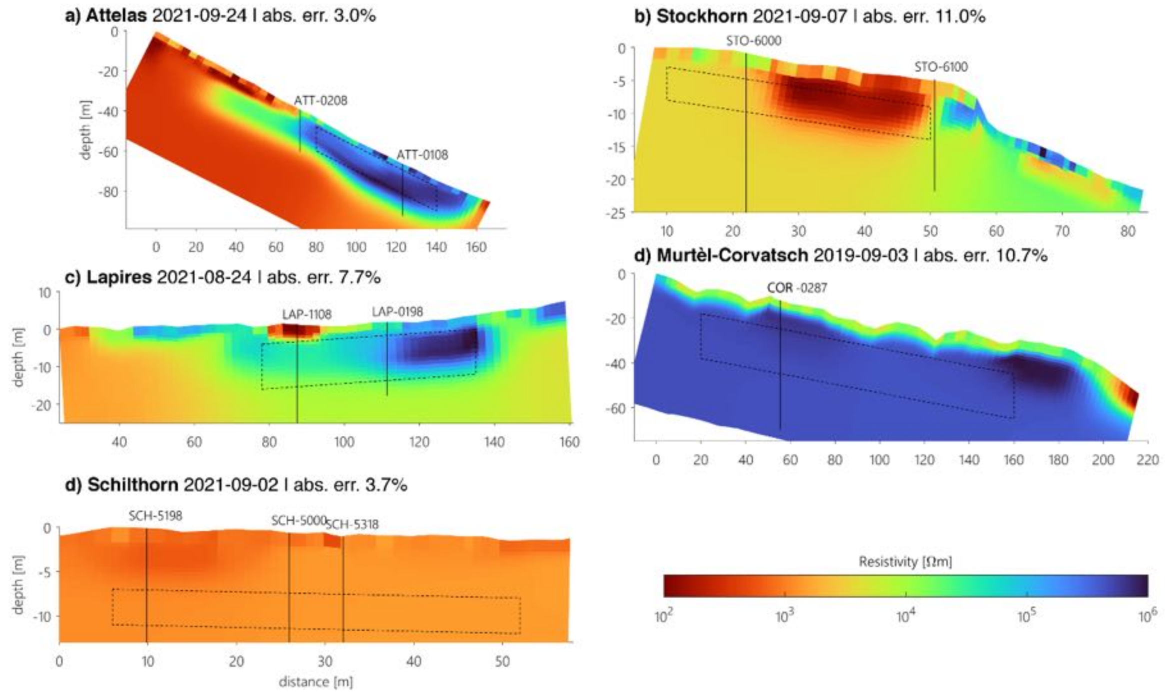

Figure 4.2: Electrical Resistivity Tomograms showing the resistivity distribution in 2021 at the five ERT profiles (note the different year at Murtèl-Corvatsch because of poor data quality in 2020 and 2021). The representative zones used for the time series in Figure 4.3 are indicated with dashed boxes and the borehole positions are indicated with vertical black lines.

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 sustained increase in unfrozen water content within the permafrost layer, which is considered a direct consequence of ground ice degradation.

In 2021, observed signals were heterogeneous: compared to 2020, resistivities slightly decreased at Schilthorn (SCH) and Stockhorn (STO), whereas they slightly increased at Attelas (ATT) and Lapires (LAP). At Murtèl-Corvatsch (COR), the insufficient data quality in 2020 and 2021 does not allow to further analyse the trend. The heterogeneous results are consistent with the reported thermal conditions in 2021 (see Chapter 3) as well as with the different sub-surface properties and topographical settings. Schilthorn and Stockhorn are both bedrock sites located on mountain plateau/ridge, with typically low ice content and where ground temperatures are mostly controlled by conductive heat transport. In 2021, record ALT was observed at Schilthorn and record-high temperatures were registered at 10 and 20 m depth at Stockhorn. Both observations are consistent with the reported resistivity decrease at the two sites. Attelas and Lapires are talus slopes composed of coarse blocks with large interconnected pore spaces, which have a ground ice content that is considerably higher than bedrock sites. Here, conductive heat transport is less efficient than at bedrock sites and heat convection/advection due to ventilation processes can take place. In 2021, lower ground temperatures in comparison to 2020 were measured at 10 m depth at Les Attelas and smaller ALT was observed at Lapires, which is in both cases consistent with the reported resistivity increase. However, the higher resistivity values measured in 2021 cannot be considered as a trend interruption/reversal, particularly when comparing them to the complete time series of permafrost resistivity, ground temperatures and ALT at these sites.

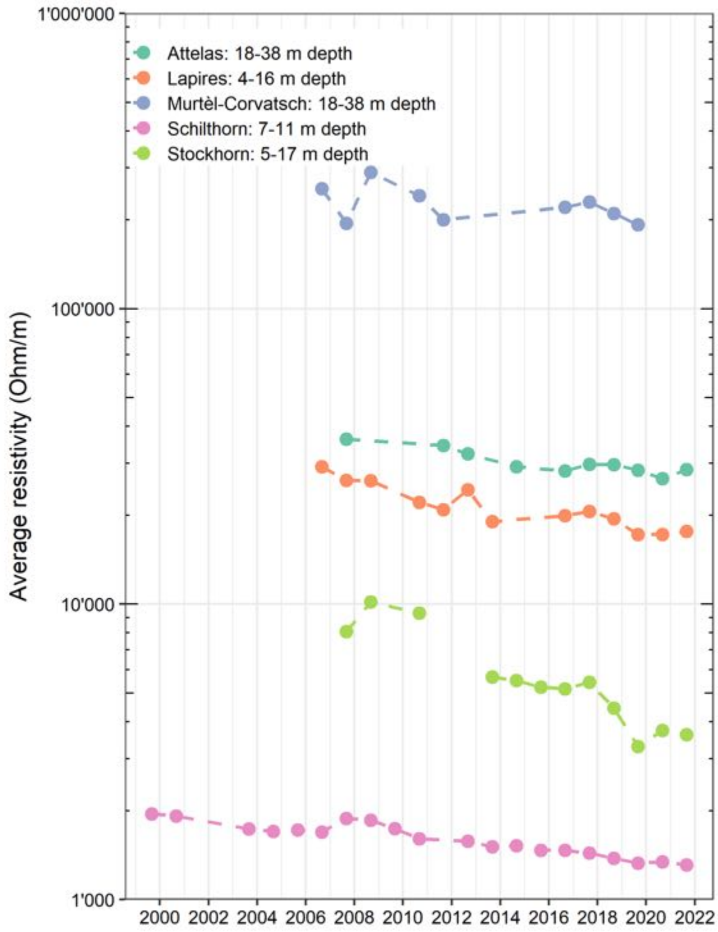

Figure 4.3: Average electrical resistivities of the permafrost zone (see Figure 4.2) at the end of summer (August–September) for the 5 ERT sites in the PERMOS Network.

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 processes sensitive to climate. Inter-annual changes in rock glacier kinematics 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). Magnitude and variability of the surface velocity of these landforms can reveal indirect information on the ground thermal regime and its evolution. Given the widespread occurrence of rock glaciers in all permafrost regions and their sensitivity to climate change, the variable rock glacier velocity (RGV) was adopted by GCOS in 2021 as a new product associated to the ECV permafrost (cf. RGIK 2022, Streletskiy et al. 2021).

Surface velocities of rock glaciers are measured by annual terrestrial geodetic surveys (TGS) at the end of summer (August-September), as well as by permanently installed GNSS devices. 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).

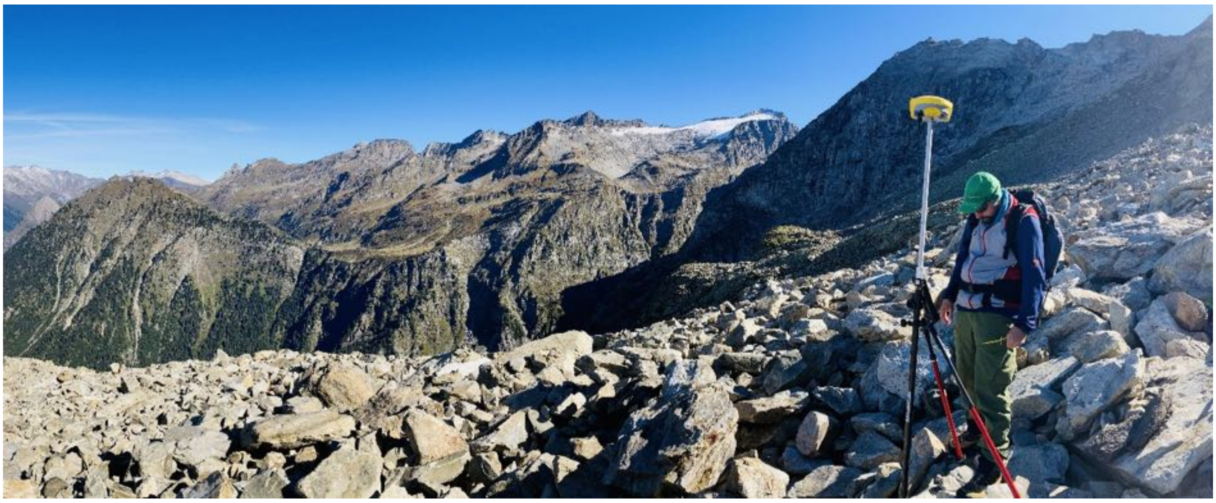

Figure 5.1. GPS measurements on the Largario rock glacier in September 2021. Photo: C. Scapozza.

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) are measured and used to calculate the surface velocity. A set of reference points is defined amongst the monitored boulders for each monitored rock glacier based on data quality and completeness as well as on the representativeness of the measured displacements. These points are used to compute site averages (Figures 5.2 and 5.3).

The hydrological year 2021 was characterized by a general velocity decrease: the mean of all sites decreased by –8.5% compared to 2020. The maximum decrease was observed at Lapires (LAP, –44%) and Grosses Gufer (GGU, –39%) located in the Lower and Upper Valais regions, respectively. In the Engadine and the Central/Southern Alps, the velocity decrease was less marked and the velocity of some rock glaciers even increased (Corvatsch, COR +5%, Figure 5.2d, and Sceru, SCE +27%, Figure 5.2c). The observed velocity decrease is consistent with the lower MAGST when compared to 2020 (see Chapter 3). The regional difference in the amplitude of velocity decrease can be attributed to the difference in snow cover (the highest snow cover was measured in Eastern and Central/Southern Switzerland, see Chapter 2).

Overall, a consistent 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.

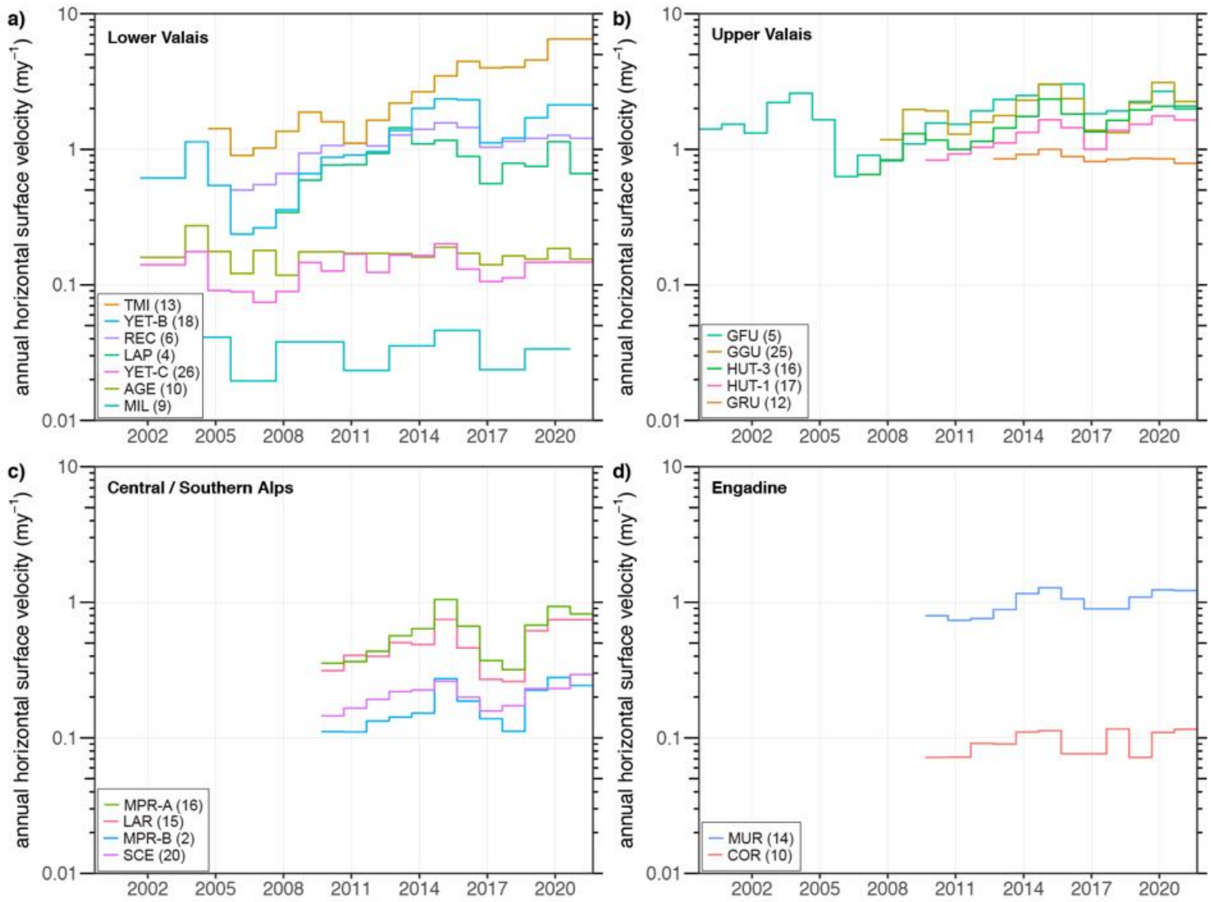

Figure 5.2: Pattern of horizontal surface velocity of 18 rock glacier lobes in the Swiss Alps, divided into four topo-climatic regions indicated in bold script. The number of reference points for each site is indicated in brackets. The abbreviations for the site names can be found in Table A.1.

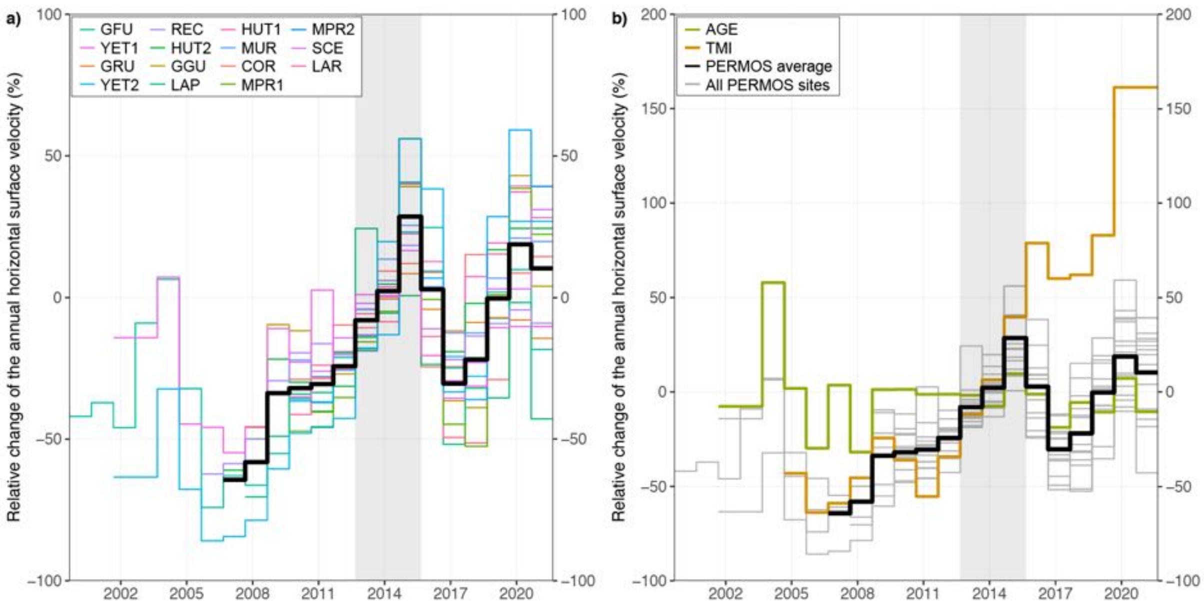

Figure 5.3: Mean annual horizontal surface velocity derived from terrestrial geodetic surveys relative to the reference period 2012–2015 (grey area). The black line represents the average of the Swiss Alps (excluding Tsarmine (TMI) and Aget (AGE)). a) 15 monitored rock glacier lobes (for site abbreviations see Table A.1). b) 2 atypical rock glaciers. Note the different scale in a) and b).

Two rock glaciers do not follow this general pattern. Since 2015, rock glacier Tsarmine (TMI, Figure 5.4) is accelerating more strongly and rock glacier Aget (AGE) is showing a decelerating trend since the start of the measurements (Figures 5.3b). However, 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, ground temperature, geometry, debris loading, etc.) become dominant and the inter-annual variations in rock glacier velocity are no longer predominantly driven by the climate.

Figure 5.4. Tsarmine rock glacier in the Arolla Valley (VS). Photo: M. Phillips.

5.2 Seasonal rock glacier velocity

Permanent GNSS measure hourly positions of single boulders on 8 rock glaciers of the PERMOS Network. The high temporal resolution provided by these instruments enables the computation of monthly to daily displacements (depending on the absolute velocity of the rock glacier), which are complementary to the annual TGS data. Small velocity variations (smaller than +/-0.1–0.2 my^{-1}) have to be interpreted with caution as they depend on a wide range of factors (e.g., snow pressure on the GNSS mast in winter, stability of the boulder in the terrain), they may not be representative of the general rock glacier motion (e.g., Wirz et al. 2014). To ensure the reliability of the short-term velocity variations, positions are filtered and subsequently aggregated using a 30-day moving window. The displacements are calculated over a 30-day period.

The seasonal evolution of RGV at three sites are shown in Figure 5.4: 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: decreasing velocities in winter (minima reached in April) followed by a strong acceleration at the beginning of summer (during snow melt) and peak velocities 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.

During the period 2017–2020, velocities increased at Grosses Gufer and Monte Prosa, whereas they remained in the same range at Gemmi. In 2021 the most pronounced winter velocity decrease since 2017 was observed as well as the least marked velocity increase following the snow melt in April. Both observations are consistent with GST (see Chapter 3).

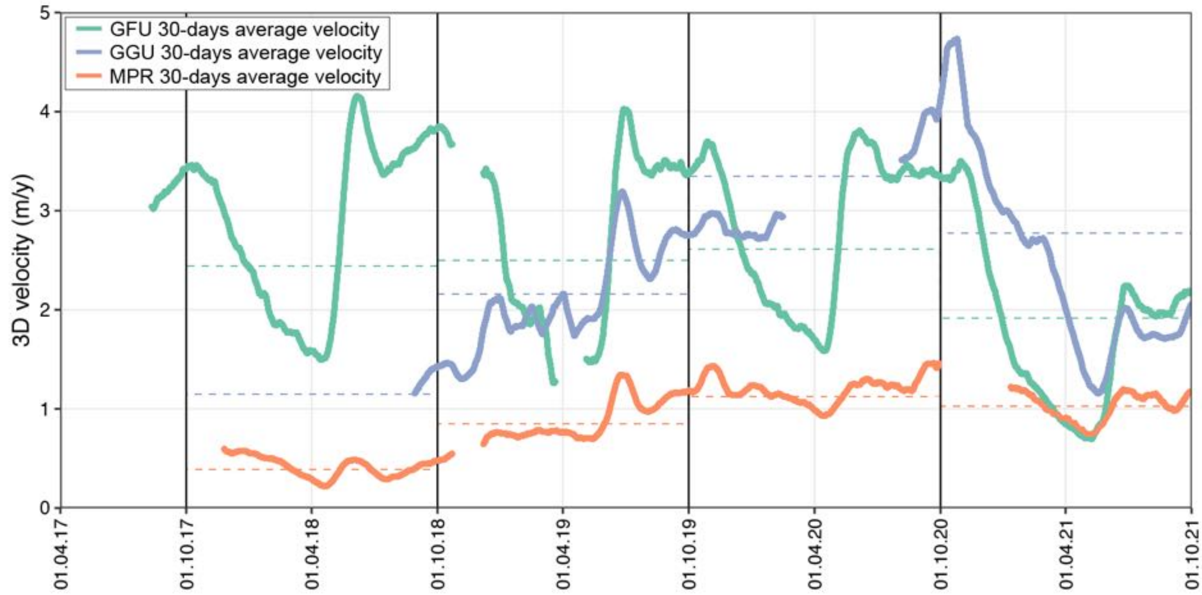

Figure 5.4: Evolution of the seasonal creep velocity at the Gemmi (green), Grosses Gufer (blue) and Monte Prosa (orange) rock glaciers. The velocities are computed over a 30-days period using 30-days averaged positions. The dotted lines represent the annual surface velocity measured at the nearest boulder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

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. Considering the entire time series since the start of the measurements, all observations show a consistent trend of continued warming and degradation of permafrost in the Swiss Alps. This general trend is marked by inter-annual variations in response to annual meteorological conditions. The permafrost conditions during the hydrological year 2021 were characterized by colder conditions in the uppermost metres of the ground and continuously increasing permafrost temperatures at depth. Active layer thickness, electrical resistivities and rock glacier velocities point to colder or similar conditions compared to the previous year, but are still above average for the entire observation period.

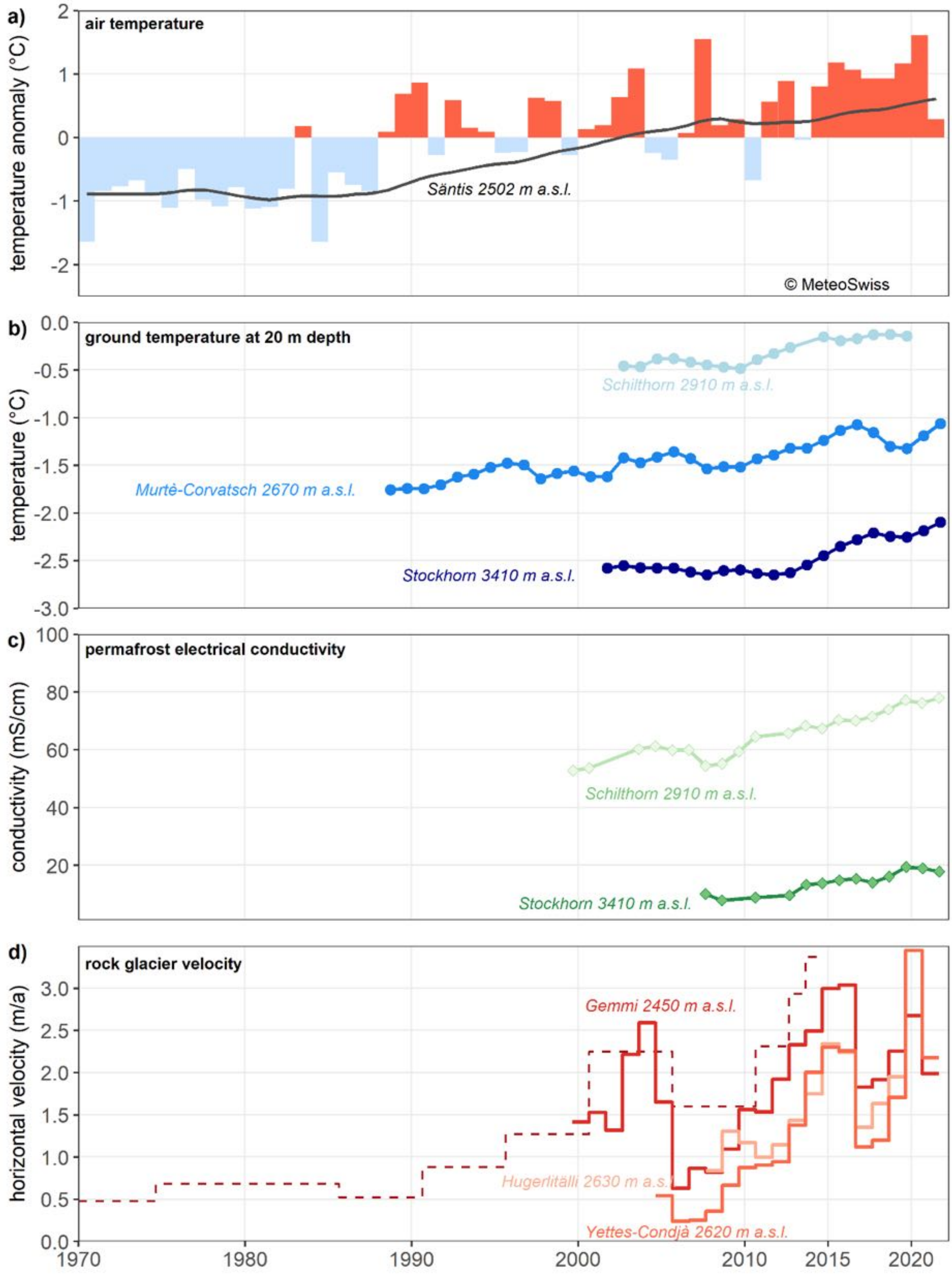

Figure 6.1: *Evolution of the three observation elements of PERMOS: annual mean permafrost temperatures at 20 m depth (b), permafrost electrical conductivity (c), and rock glacier creep velocity (d). The dashed red line represents the horizontal surface velocity for Gemmi obtained by aerial photogrammetry.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

The air temperature during the hydrological year 2021 was 0.3 °C above the climatic norm 1981–2010, making 2021 the coldest year since 2013. It was characterized by a warm winter with a long-lasting snow cover, a cold spring, a wet summer and a dry and sunny autumn. Snow height was above average in Eastern and Central/Southern Switzerland and average in Western Switzerland. The weather and climate conditions lead to the following permafrost conditions in the Swiss Alps during the hydrological year 2021 (Figure 6.1):

- Ground surface temperatures were lower in 2021 compared to previous years due to lower air temperature in spring and summer and a long-lasting snow cover.
- ALT observed in 2021 were heterogeneous with greater values than 2020 at 4 sites and smaller values at 5 sites. New records values were registered at two sites.
- The permafrost temperatures measured at 10 m depth were partly influenced by the lower GST in 2021 and a slight decrease or stable temperatures were observed in about half of the boreholes. At 20 m depth, permafrost temperatures have not (yet) been affected by the cooling at the surface and continued to increase compared to the previous year at all sites. At some sites, new record values have even been reached.
- Heterogeneous signals of permafrost electrical resistivities were observed at five sites in 2021 with both resistivity increases and decreases. The talus slope sites were most affected by ground surface temperature cooling and exhibited resistivity increase, whereas at the bedrock sites the resistivities decreased.
- A decrease of rock glacier velocity by –8.5% (Swiss average, maximum recorded –44%) compared to 2020 was measured. The signal is regionally heterogeneous with more pronounced decreases in the Lower and Upper Valais (Western Switzerland) and only small changes in the Engadine and Central/Southern Alps regions.

Overall, the hydrological year 2021 was characterized by colder conditions at the surface and in the uppermost metres of the ground (lower GST and lower creep velocities) and a continued increase of the permafrost temperatures at larger depth. The results from the active layer thickness, temperature measurements at 10 m depth and electrical resistivities were heterogeneous.

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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		